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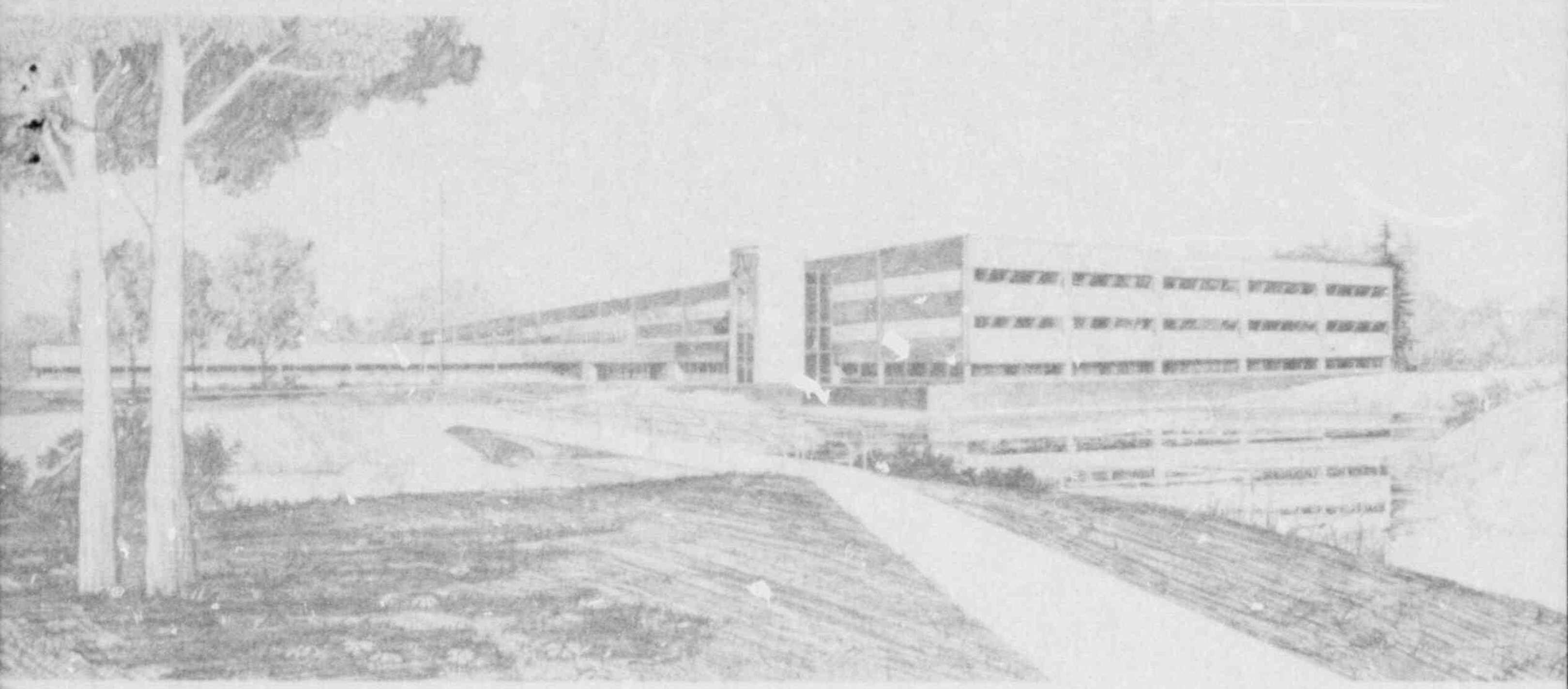

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ABSTRACT

A device was developed to measure voiding on the primary side of a U-tube steam generator. This device is known as a Boundary Layer Voiding Detector (BLVD) and consists of a heating coil wrapped around a single U-tube with a thermocouple placed between the heating coil and the U-tube wall. Loss of fluid on the primary side of the U-tube can cause a significant increase in temperature thus indicating voiding. Two computer models were developed to simulate the transient and steady state responses, respectively. Low-pressure and temperature testing was also performed to verify BLVD operation. When highly subcooled conditions exist, this device can detect primary side voiding. When the fluid is near saturation and boiling can occur, void detection is considerably more difficult. The large heat transfer coefficients associated with the boiling process produce significant heat transfer without a measurable temperature increase.

LOFT Experimental Instrumentation FIN No. A6043

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THE MODELING AND TESTING OF A HEATED BOUNDARY LAYER VOIDING DETECTOR

INTRODUCTION

A Loss of Coolant Accident (LOCA) in a nuclear reactor may require shutdown of the main coolant pumps to prevent pump cavitation and avoid direct discharge of the coolant through the break. Natural circulation is then used to remove the reactor's decay heat. Conditions for natural circulation must be established and continued for safe reactor cooldown.

Natural circulation results from the density head produced by the cooling of the primary side fluid in the steam generators. The reactor's decay heat reduces the fluid density at an elevation below the steam generators. Higher density fluid then moves to replace the lower density fluid present in the reactor core resulting in a low-velocity flow through the reactor's primary system. This flow is usually sufficient to provide adequate long-term reactor cooling for the typical Pressurized Water Reactor (PWR) system shown in Figure 1.

Noncondensible gases can originate from fission gases in the fuel pins, the hydrolysis of coolant, or from the coolant directly. These noncondensible gases can hinder or stop natural circulation. The gases tend to migrate to the highest elevation in the reactor system, i.e., the top of the steam generator U-tubes, shown in Figure 2. At this point, the gases can decrease the heat transfer rate and reduce the driving head enough to stop natural circulation. The loss of cooling capability would result in core overheating.

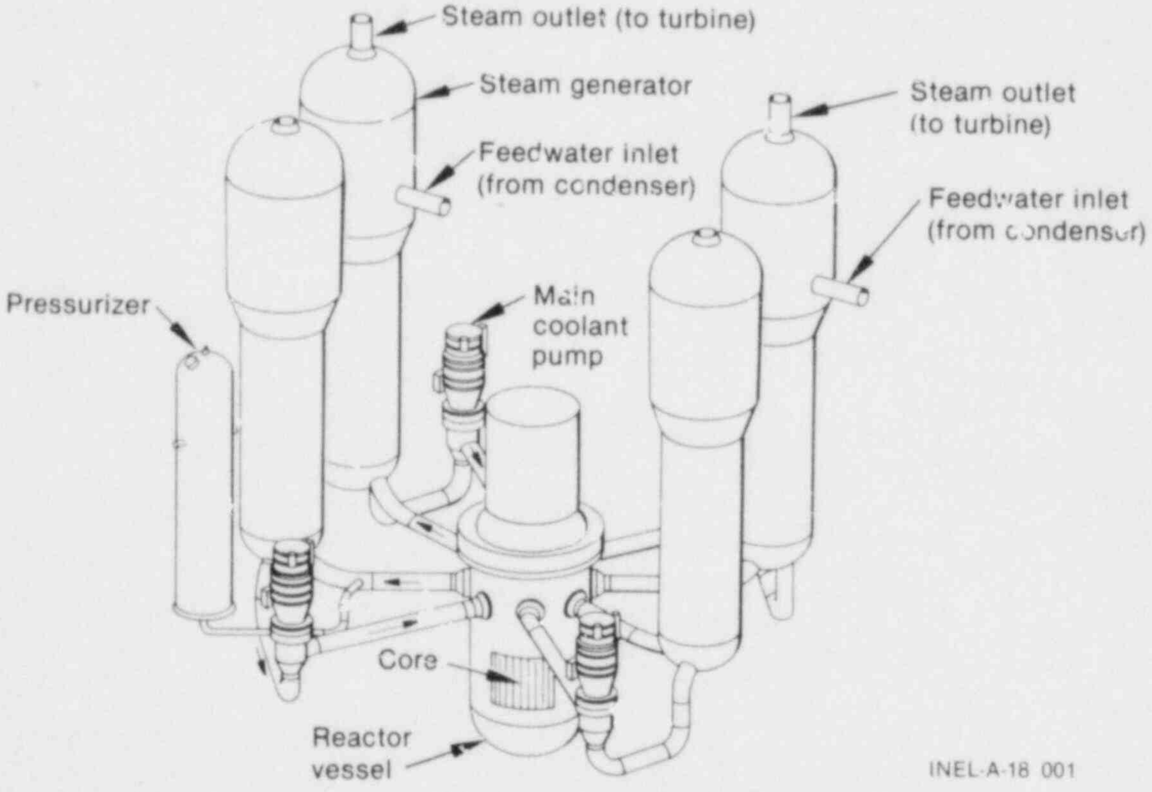

Figure 1. Schematic arrangement of PWR nuclear steam supply system (NSSS).

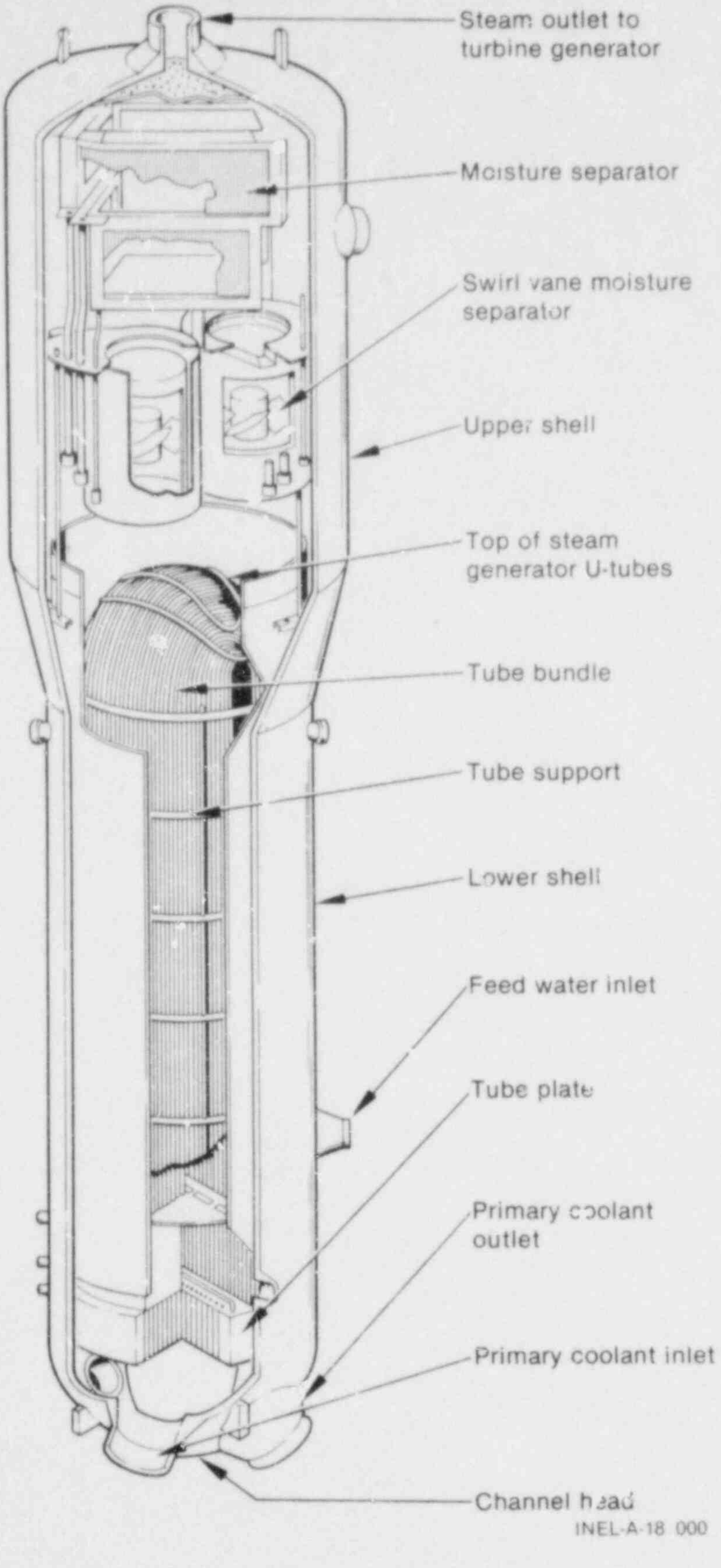

Figure 2. PWR steam generator.

The existence of natural circulation can be determined by measuring the flow of the primary coolant at the top of the PWR steam generator U-tubes. Laube[1] has demonstrated a heated device for nonintrusively measuring a fluid's velocity. Only the boundary layer of the fluid is heated, thus minimizing flow disturbance by the device.

A similar technique can be applied for flow or voiding detection in the U-tubes of a commercial PWR. A resistance heater is wrapped around a small section of the U-tube, with the heater temperature being monitored by a thermocouple placed on the tube surface under the heater. Lack of coolant flow or voiding should produce a significant rise in heater temperature. This device is known as a Boundary Layer Voiding Detector (BLVD).

A three step procedure was undertaken to develop and test a BLVD for application on the U-tubes of PWR steam generator. Initially, a lumped parameter model was developed to calculate the sensitivity and transient response of this device. A steady state model using a series of one-dimensional relaxation equations was then formulated to assess the axial temperature distribution and evaluate the applicability of the lumped parameter transient model. Finally a BLVD was installed on a Semiscale size U-tube and tested at atmospheric pressure. These tests demonstrated that a heated BLVD can detect voiding only when large subcoolings are present. The large heat transfer rates associated with boiling were found to prevent voiding detection by the BLVD under two-phase conditions.

MODELING TECHNIQUES

Two techniques were employed to calculate the operational characteristics of a BLVD. A lumped parameter model[2] was used to calculate the device's sensitivity as well as its transient response. One-dimensional relaxation equations[2] were used to calculate the axial steady state temperature distribution along the U-tube wall. A number of heat transfer correlations from published literature were employed to calculate single phase and boiling heat transfer coefficients. Both techniques were computerized to permit rapid assessment of the BLVD under various conditions.

Transient Model

The lumped parameter model was derived from a simple heat balance. Rate of Creation (ROC) principles are applied as follows:

$$\left\{\begin{matrix}\text{Rate of}\\ \text{energy inflow}\end{matrix}\right\} - \left\{\begin{matrix}\text{Rate of}\\ \text{energy outflow}\end{matrix}\right\} = \left\{\begin{matrix}\text{Rate of}\\ \text{energy storage}\end{matrix}\right\}. \qquad (1)$$

Applying Equation (1) to the BLVD shown in Figure 3 produces:

$$\overbrace{VId\theta}^{\substack{\text{Heater}\\ \text{power}}} - \overbrace{[h_pA_p(T - T_p)d\theta + h_sA_s(T - T_s)d\theta]}^{\text{Convective heat transfer}} = \overbrace{c_p\rho v dT}^{\substack{\text{Heating of}\\ \text{BLVD}}} \qquad (2)$$

where

V = heater voltage, volts

I = heater current, amps

h_p = primary side heat transfer coefficient, W/cm^2-°C

h_s = secondary side heat transfer coefficient, W/cm^2-°C

θ = time, s

T = temperature of BLVD, °C

A_p = primary side heat transfer area, cm^2

A_s = secondary side heat transfer area, cm^2

T_p = primary side bulk fluid temperature, °C

T_s = secondary side bulk fluid temperature, °C

c_p = heat capacity of BLVD, W-s/g-°C

ρ = density of BLVD, g/cm^3

v = volume of BLVD, cm^3.

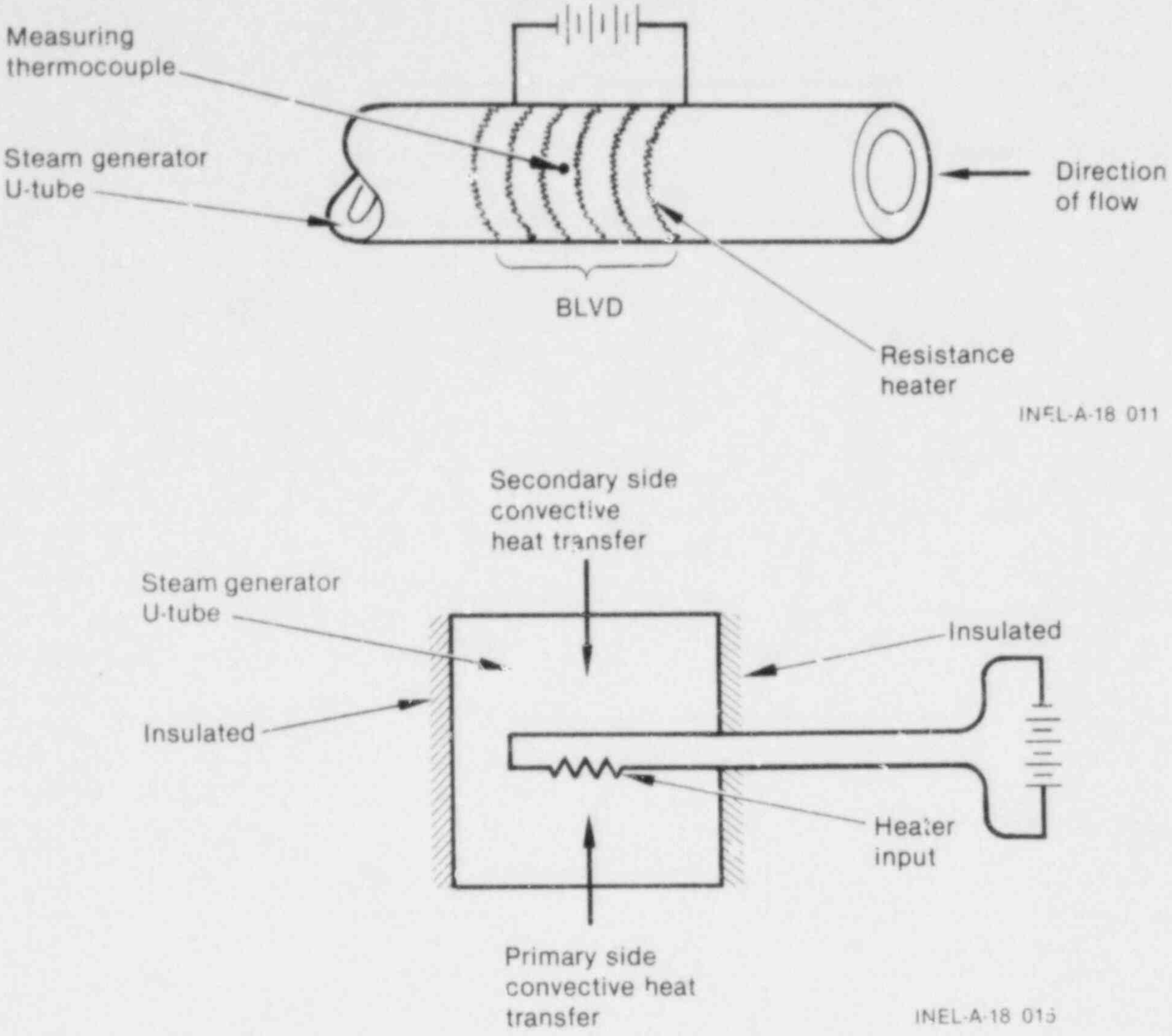

Figure 3. BLVD schematic and lumped parameter heat transfer model.

This expression is algebraically rearranged to separate the time and temperature variables.

$$d\theta = -c_p \rho V \frac{dT}{(h_p A_p + h_s A_s)T - (VI + h_p A_p T_p + h_s A_s T_s)} . \tag{3}$$

Equation (3) can be exactly integrated since

$$\int \frac{dx}{ax - b} = \frac{1}{a} \ln(ax - b) \tag{4}$$

for $x \neq b/a$

and assuming that the physical properties of the BLVD and associated heat transfer coefficients are constant. The temperature of the BLVD as a function of time is

$$T(\theta) = \frac{M_s(T_i - T_s) + N_p(T_i - T_p) - VI}{M_s + N_p} \exp\left[- \frac{(M_s + N_p)\theta}{c_p \rho V} \right] + \frac{VI + M_s T_s + N_p T_p}{M_s + N_p} \tag{5}$$

where

$T(\theta)$ = BLVD temperature as a function of time, °C

M_s = $h_s A_s$, W/°C

N_p = $h_p A_p$, W/°C

T_i = initial temperature of BLVD, °C.

Most of the constants in this equation can be readily measured. The heat transfer coefficients, however, must be calculated from correlations of previous data. A later part of this report will describe the specific empirical correlations used.

Hand evaluation of Equation (5) as a function of time would be a tedious task. This equation was assembled into a small computer code to permit rapid evaluation. In addition, the auxiliary calculations for heat transfer coefficient (HTC) and area of heat transfer are performed quickly and accurately. The code prompts the user for the necessary input parameters, making the analysis of parameter variations easy. A flowchart of the lumped parameter transient simulation is illustrated in Figure 4. Appendix A contains a listing of the lumped parameter model program as well as a sample output.

The validity of lumped parameter technique can be estimated by calculating the Biot modulus. This parameter is a ratio of the convective to conductive heat transfer ability of a system and is shown in Equation (6).

$$Bi = \frac{hL}{k_s}. \tag{6}$$

where

h = total convective heat transfer coefficient, W/cm^2-°C

L = characteristic length, volume to heat transfer area ratio, cm

k_s = BLVD thermal conductivity, W/cm-°C.

If the Biot modulus is less than 0.1, lumped parameter models are generally adequate. Calculations indicate that the BLVD's Biot modulus is usually less than 0.1 as long as single phase conditions prevail. Boiling heat transfer coefficients are usually very large, thus the lumped parameter model will not be applicable.

Steady State Model

The steady state axial temperature distribution along a single steam generator U-tube was calculated using a one-dimensional relaxation technique. The BLVD and the U-tube were simulated as a one-dimensional horizontal strip, shown in Figure 5. Modeling of the detector and U-tube assumes that the

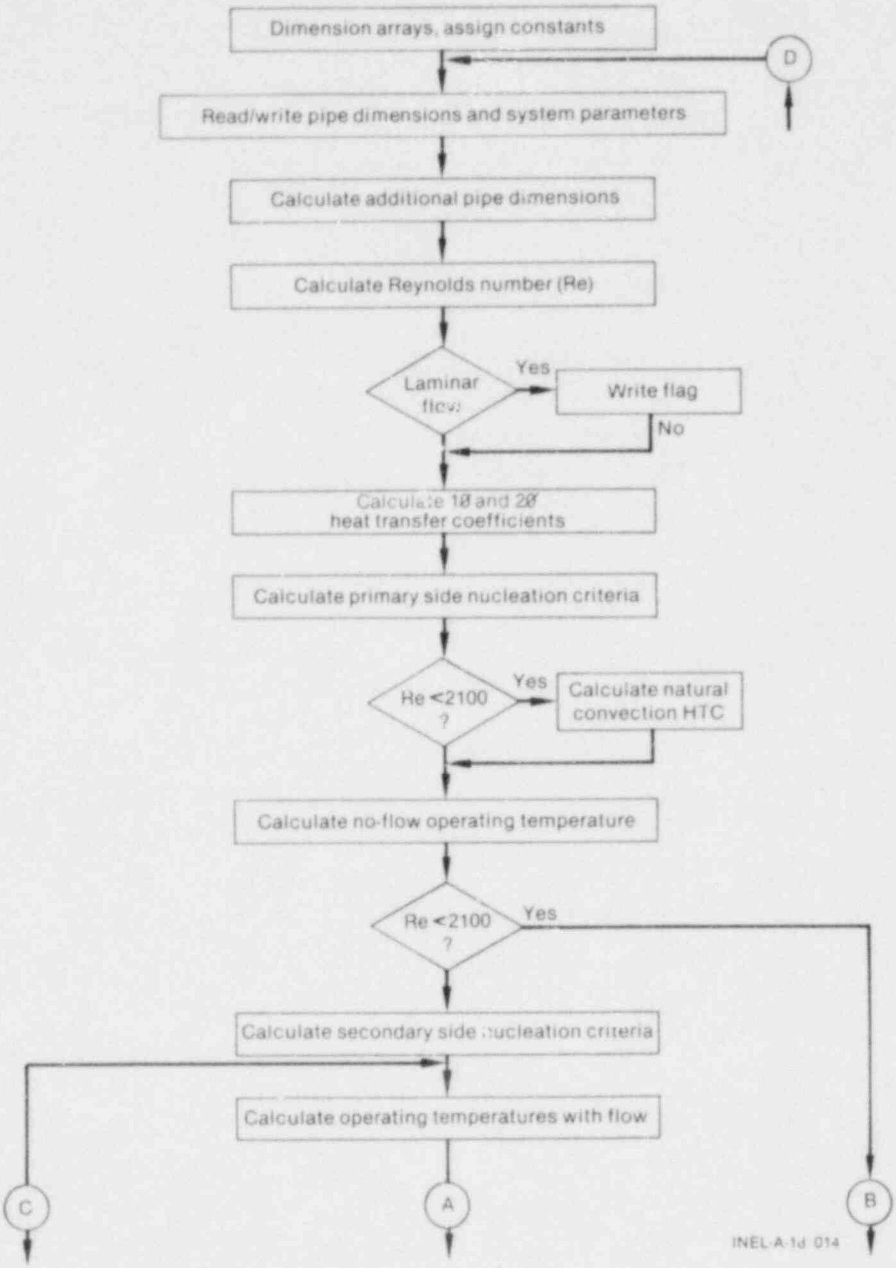

Figure 4. A flowchart of the B[illegible]VD lumped parameter transient computer model.

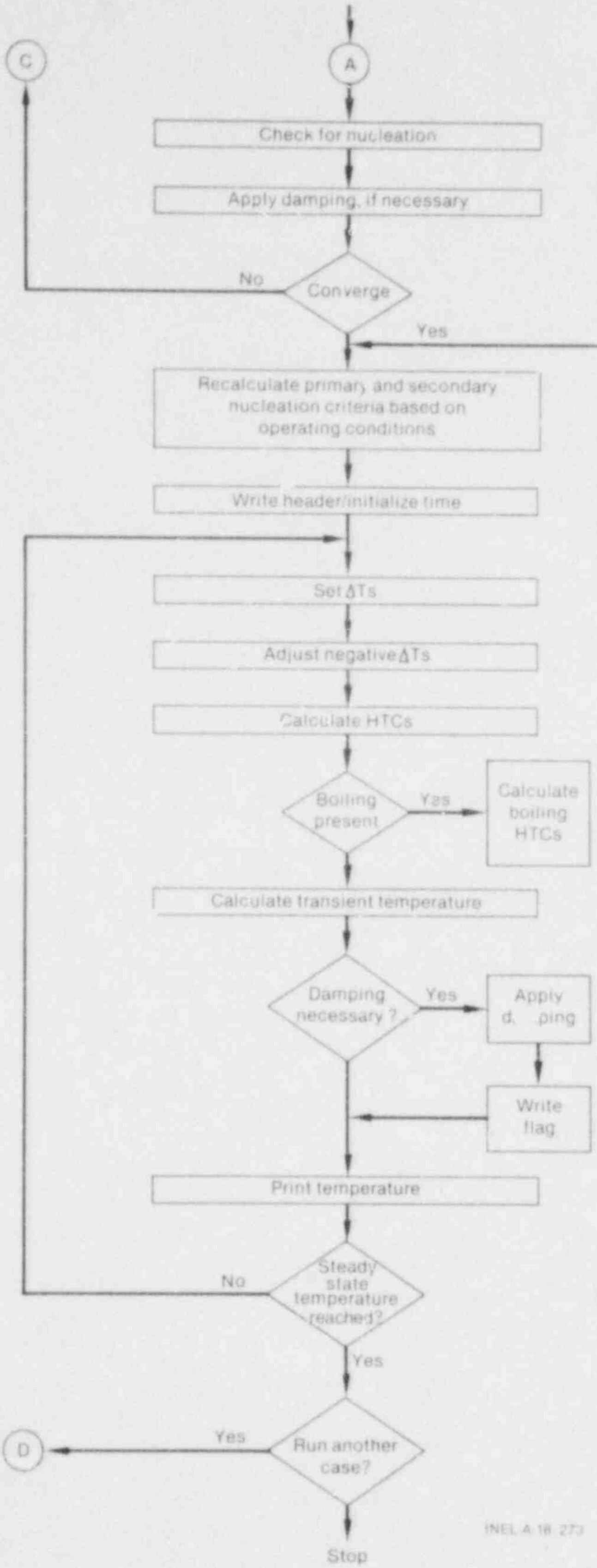

Figure 4. (continued).

system can be represented by a series of nodes. The local heat flow at each node can be calculated from a simple heat balance. Newton's Law of Cooling, Equation (7), and Fourier's Law for Heat Conduction, Equation (8), are applied at each node.

$$\frac{q}{A} = h\Delta T \tag{7}$$

$$\frac{q}{A} = -k\frac{\Delta T}{\Delta x} \tag{8}$$

where

$\frac{q}{A}$ = heat flux, W/cm^2

h = convective heat transfer coefficient, W/cm-^{2}°C

ΔT = temperature difference, T_{wall}-T_{bulk}, °C

k = thermal conductivity, W/cm-°C

$\frac{\Delta T}{\Delta x}$ = temperature gradient, °C/cm.

The heat flow is balanced at each node, m, by appropriate combinations of Equations (7) and (8).

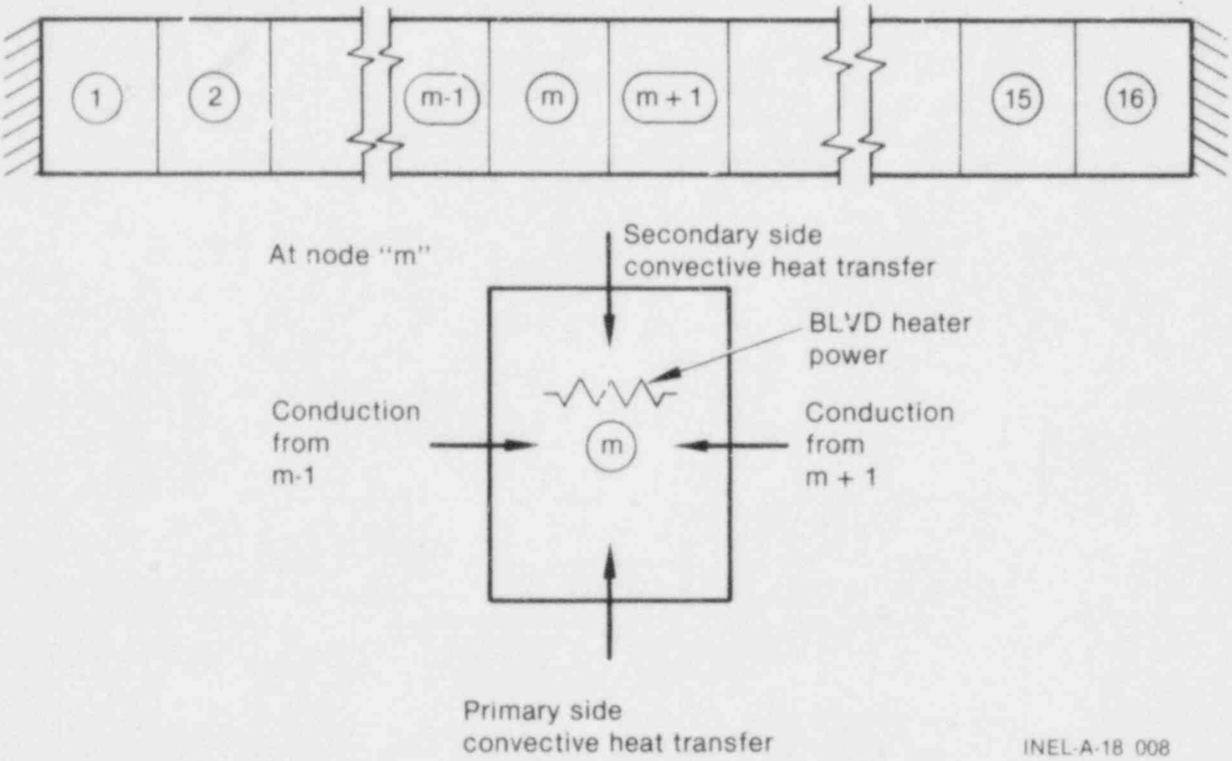

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Figure 5. BLVD steady state nodal relaxation model.

$$\begin{aligned}&\overbrace{W_m}^{\text{Generated Heat}} + \overbrace{K(T_{m-1} - T_m) + K(T_{m+1} - T_m)}^{\text{Conduction}} \\ &\quad + \underbrace{M_s(T_s - T_m) + N_p(T_p - T_m)}_{\text{Convection}} = \underbrace{Q_m}_{\text{Residue}}\end{aligned} \qquad (9)$$

where

W_m = heat generated by BLVD, W

$K = \frac{kA}{\Delta x}$, W/°C

$M_s = h_s A_s$, W/°C

$N_p = h_p A_p$, W/°C

Q_m = residue, W

T_m = temperature, °C.

Nodes located at the two ends of the strip are only half the length of other nodes and have an insulated side. Equations (10) and (11) describe the first and last nodes, respectively.

$$2K(T_{m+1} - T_m) + \frac{M_s}{2}(T_s - T_m) + \frac{N_p}{2}(T_p - T_m) = Q_m \qquad (10)$$

for $m = 1$

$$2K(T_{m-1} - T_m) + \frac{M_s}{2}(T_s - T_m) + \frac{N_p}{2}(T_p - T_m) = Q_m \qquad (11)$$

for $m = 16$.

Relaxation techniques can be used to solve the set of equations described by Equations (9), (10), and (11). An initial temperature distribution is assumed. The heat transfer coefficients described in the next section are used. Residues are calculated for each node. The largest residue is selected, and the temperature at that node is adjusted to reduce the residue to zero. Residues adjacent to this node are recalculated using the new temperature at node m. The next largest residue is then selected and the process repeated. These iterations are continued until all residues are reduced below a previously specified minimum.

Selection of an initial temperature distribution that is close to the final distribution speeds the convergence of the relaxation but is not necessary. Any temperature distribution will eventually be relaxed to the correct distribution, however the number of iterations will increase substantially for a poorly selected temperature distribution.

Because a large number of equations must be solved simultaneously, a computer code was developed. The code takes the initial temperature distribution guess and iterates until the largest residue is reduced below a user specified minimum. In addition, the auxiliary calculations for heat transfer coefficient and area of heat transfer are performed quickly and accurately. The code prompts the user for the necessary input parameters, making variation of parameter studies easy. A flow chart of the steady state one-dimensional relaxation model is illustrated in Figure 6. Appendix B contains a listing of the relaxation program as well as a sample output.

Heat Transfer Coefficients

Many heat transfer correlations are available in the literature for natural and forced single phase convection. The Dittus-Boelter[3] correlation, Equation (12), is widely used and accepted for

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.4} \tag{12}$$

where

Nu = Nusselt number, hD/K, dimensionless

Re = Reynolds number, VD/ν, dimensionless

Pr = Prandtl number, $^{c}p^{\mu}/k$, dimensionless

h = convective heat transfer coefficient, W/cm^2-°C

D = characteristic dimension, cm

k = thermal conductivity, W/cm-°C

v = fluid velocity, cm/s

ν = kinetic viscosity, stokes

c_ρ = specific heat, W-s/g-°C

μ = absolute viscosity, centipoise.

single phase forced convection heat transfer. This expression can be manipulated to yield the convective heat transfer coefficient, h.

Correlations for the heat transfer coefficient under single phase natural convection were developed by McAdams.[4] The appropriate correlation for horizontal pipes is given in Equation (13).

$$Nu = 0.53(Gr\ Pr)^{0.25} \tag{13}$$

where

Gr = Grashof number,

$$\frac{\rho g^2 \beta (T_w - T_b) D^3}{\mu^2}\text{, dimensionless}$$

where

ρ = density, g/cm^3

g = acceleration due to gravity, 980 cm/s^2

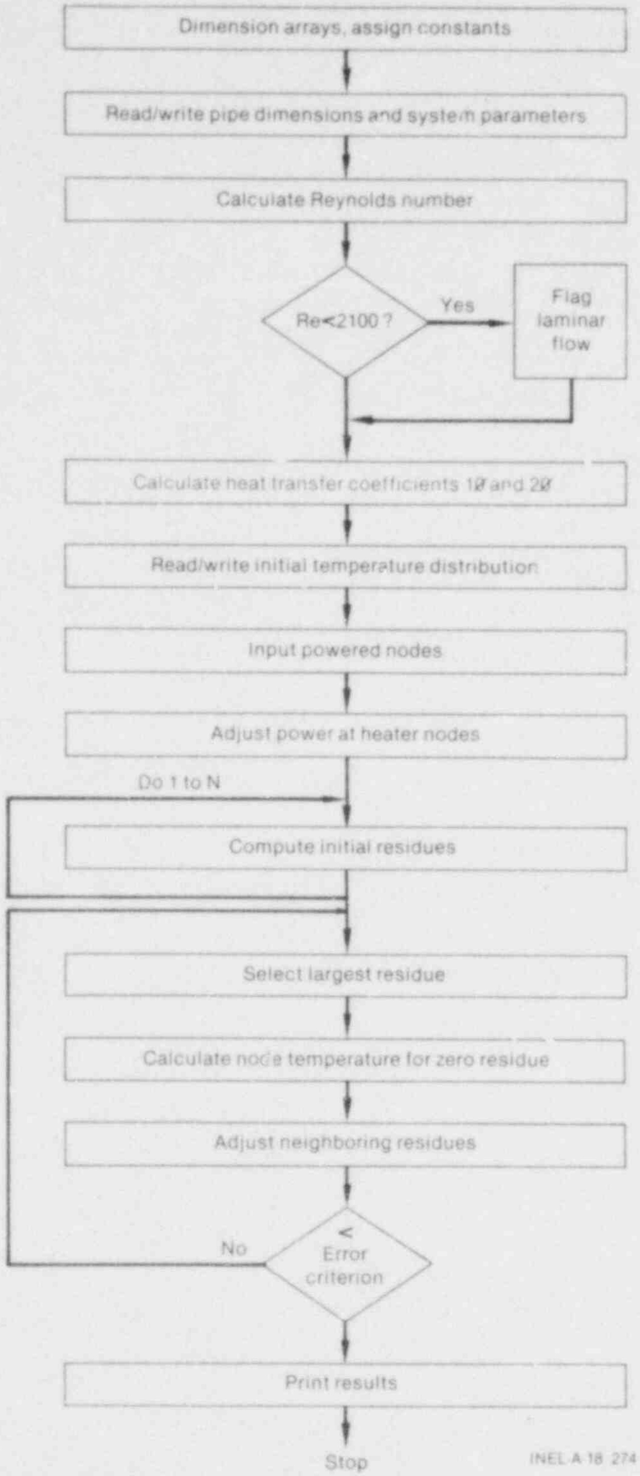

Figure 6 A flowchart of the BLVD one-dimensional relaxation computer model.

β = coefficient of thermal expansion, 1/°C

T_w = wall temperature, °C

T_b = bulk temperature, °C.

Note that this correlation has a weak dependence on the driving temperature difference. Since the relationship is weak it is possible to use this heat transfer coefficient in Equation (5) without violation of the initial assumptions that the BLVD and associated heat transfer coefficients are constant.

Boiling heat transfer was also considered. The pooling and flow boiling heat transfer coefficients are calculated from correlations in the literature. Jens and Lottes[5] have proposed an expression which relates the heat flux to the pressure and temperature.

$$\frac{q/10^6}{A} = \left[\frac{\exp^{p/900}}{60}\left(T_w - T_{sat}\right)\right]^4 \tag{14}$$

where

q = heat rate, Btu/min

A = area of heat transfer, ft^2

p = system pressure, psia

T_w = wall temperature, °F

T_{sat} = saturation temperature, °F.

The heat transfer coefficient is calculated by substituting Equation (14) into Equation (15),

$$\frac{q}{A} = h\left(T_w - T_\infty\right) \tag{15}$$

yielding

$$h = \frac{\left[\frac{\exp^{p/900}}{50}\left(T_w - T_{sat}\right)\right]^4 \times 10^6}{T_w - T_\infty} . \tag{16}$$

Rosenhow[6] has correlated substantial pool boiling data with Equation (17).

$$\frac{c_{p\ell}\left(T_w - T_{sat}\right)}{h_{fg} Pr_\ell^{1.7}} = C_{sf}\left[\frac{q/A}{\mu_\ell h_{fg}}\sqrt{\frac{g_c \sigma}{g\left(\rho_\ell - \rho_g\right)}}\right]^{0.33} \tag{17}$$

where

$c_{p\ell}$ = specific heat of saturated liquid, Btu/lbm-°F

h_{fg} = heat of vaporization, Btu/lbm

g_c = conversion factor, 32.2 lbm/ft/lb$_f$/sec^2

g = acceleration due to gravity, 32.2 ft/sec^2

σ_ℓ = surface tension of the liquid-to-vapor interface, lb$_f$/ft

μ_ℓ = viscosity of liquid, lbm/hr-ft

C_{sf} = empirical constant is 0.0133 for BLVD[7]
(water on chemically etched stainless steel)

Pr_ℓ = liquid Prandtl number, dimensionless

ρ_ℓ = liquid density, lbm/ft^3

ρ_g = vapor density, lbm/ft^3.

Substitution of Equation (15) into Equation (17) will produce an expression for the heat transfer coefficient.

$$h = \frac{\mu_\ell h_{fg}}{(T_s - T_\infty)} \sqrt{\frac{g(\rho_\ell - \rho_g)}{g_c \sigma}} \left[\frac{c_{p\ell}(T_w - T_{sat})}{h_{fg} Pr_\ell^{\;1.7} C_{sf}} \right]^3 . \tag{18}$$

The total heat flux during boiling consists of two components: a single phase heat flux and a boiling heat flux. Superposition of the two heat flux components will yield the total heat flux, as shown in Equation (19).

$$\frac{q_{total}}{A} = \frac{q_{boiling}}{A} + \frac{q_{single\ phase}}{A} . \tag{19}$$

The total heat transfer coefficient to be used is calculated by substituting Equation (15) into (19), using the appropriate heat transfer coefficients from Equations (16) and (18).

Boiling heat transfer coefficients have a strong temperature dependence. A small temperature difference will produce a large heat transfer coefficient. Careful application of these correlations is necessary to maintain the initial assumptions of the transient heat transfer model.

BLVD U-TUBE TEST ASSEMBLY

A small test assembly was constructed to evaluate the performance of a BLVD in a simulated steam generator system.[a] Eight 3/4-in. diameter tubes were bent into a U-shape and installed in a manifold. This assembly was mounted in an open steel tank. The tank (413 liter) with two 5-kW heaters was used to simulate the secondary side of the steam generator. A small loop consisting of heated tank (189 liter) and a 1-hp pump was used to provide water flow to the primary side of the steam generator. An air compressor supplied air to the manifold at the base of the U-tube arrangement. This air could be used to void the U-tube bundle. Reference instrumentation included two water rotameters to measure primary side flowrate, and Type-K thermocouples to measure various temperatures throughout the system. A data logger and strip chart recorder were used to collect the thermocouple data.

The primary loop's pump can supply water flowrates ranging from 0.063 to 0.88 l/s resulting in liquid superficial velocities of 0.29 to 4.1 m/s for a single U-tube. The maximum attainable system temperature was 85°C. Figure 7 shows the U-tube test assembly.

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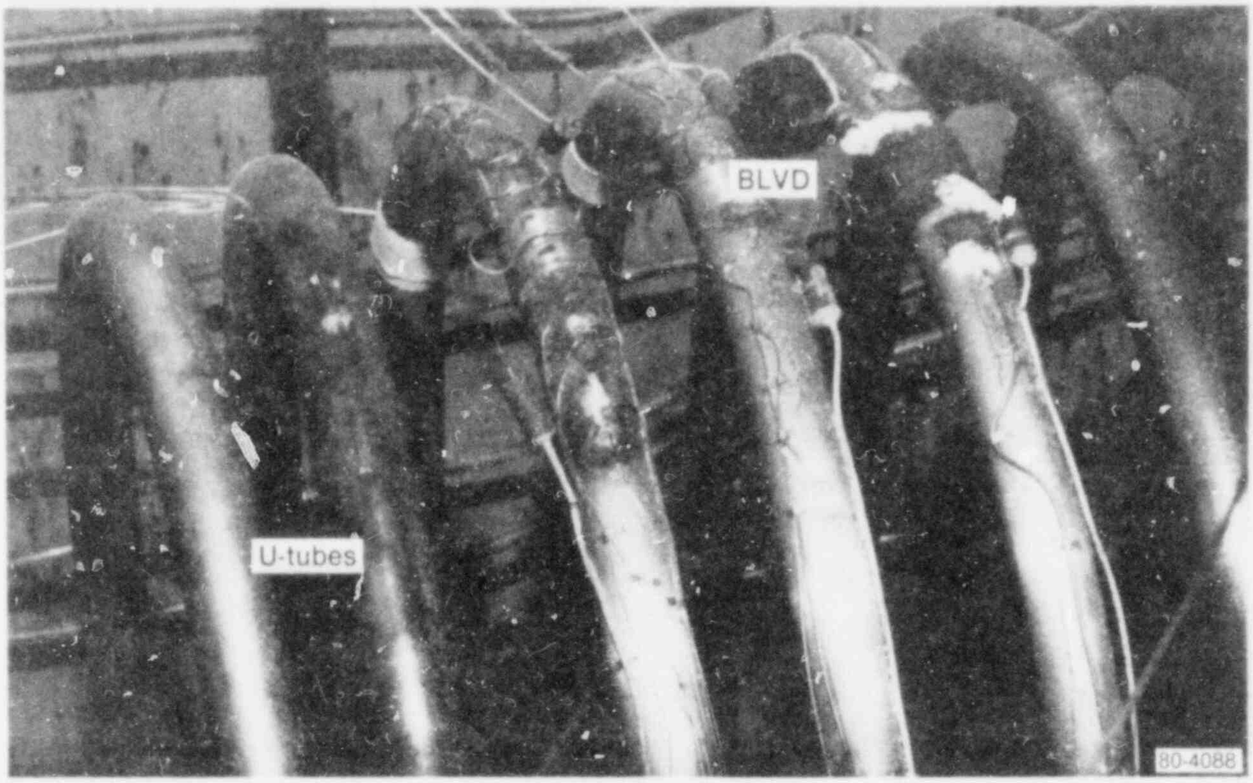
[a] The U-tubes of the Semiscale experiment were modeled in this test.



Instrumented U-tube

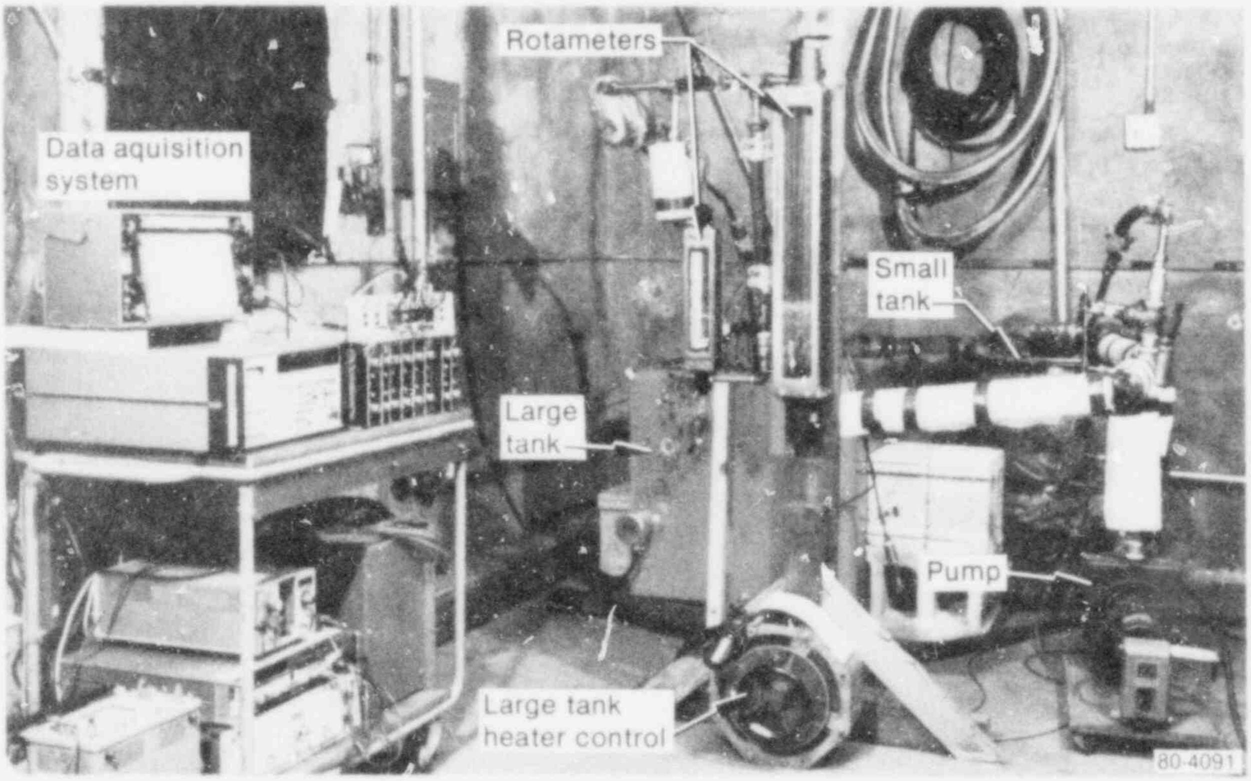


Figure 7. BLVD U-tube test assembly.

RESPONSE TIME AND BOILING EFFECTS ON THE BLVD

A series of low-pressure tests were performed to measure the response time of the BLVD and to assess its response in nucleate boiling conditions. A comparison of the predicted response with the measured response was undertaken using above derived relations.

Two types of tests were conducted:

1. A pump coastdown, where the primary side pump was shut off and allowed to coast to a stop
2. Voiding by injection of room temperature air after a pump shutdown.

Tests were performed at temperatures of 20°C and 80°C for bare and secondary side insulated BLVDs.

Initial testing was conducted at 16°C with a liquid superficial velocity of 2.34 m/s (8 gpm) on the primary side. The primary side pump was shut off and allowed to coast to a stop. Simultaneously, the EMF of the BLVD's thermocouple was recorded on a strip chart. Selected data points[a] from typical thermal transient is shown in Figure 8 and compared to the lumped parameter computer model prediction. Reasonably good agreement between the actual data and model is illustrated particularly after 15 s. Prior to 15 s some discrepancy is observed. Similar tests were repeated to ensure reproducibility.

The computer simulation of the transient response was not an exact duplication of the BLVD tests. Pump coastdown was modeled as an instantaneous flow stoppage while the actual flow probably followed

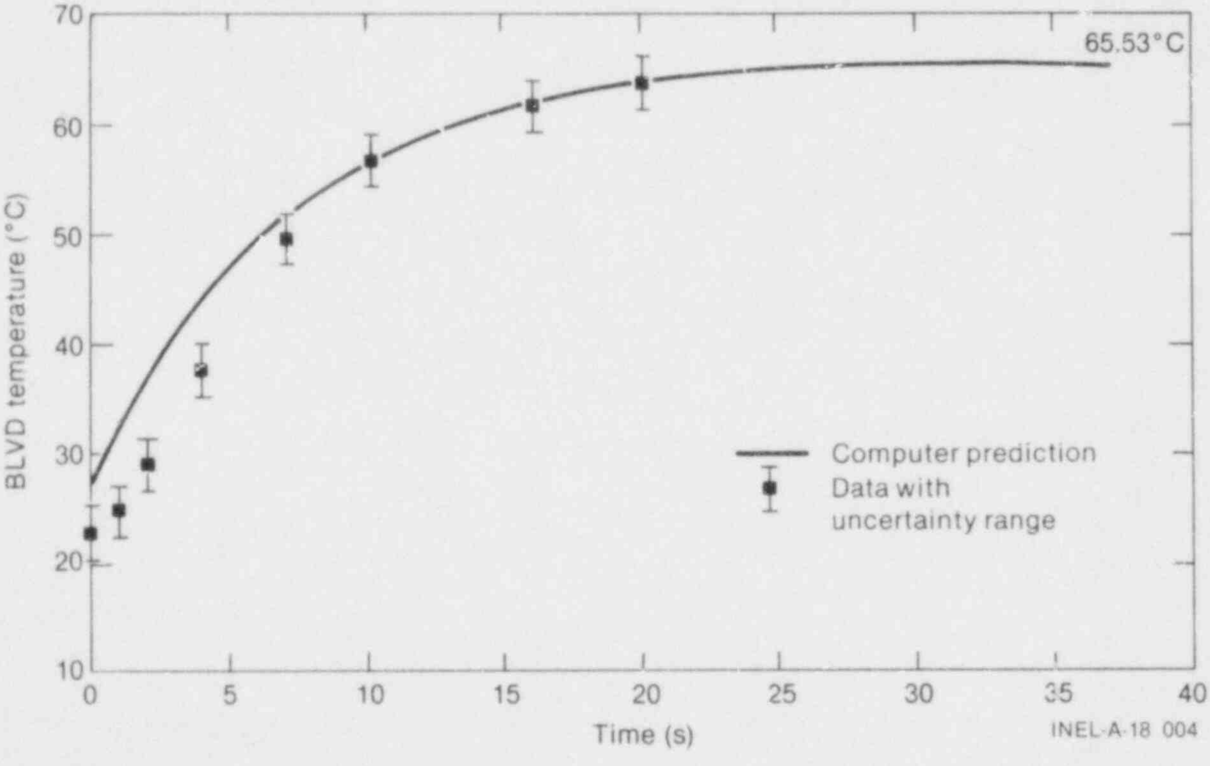


Figure 8. A comparison of the actual BLVD response to pump coastdown with the transient computer model prediction at 16°C with 0.063 l/s initial flow.

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[a] The continuous voltage of the BLVD thermocouple was recorded, but only representative points will be shown in the figures.

an exponential decay. This discrepancy produces part of the initial differences between the measured and calculated results. The simplicity of the lumped parameter model and the uncertainty in the heat transfer correlations are an additional cause of discrepency.

Two cases were run with air injection to void the top of the U-tube. As expected, air injection did produce a higher temperature at the BLVD. The results are illustrated in Figure 9. A comparison of Figures 8 and 9 indicate that U-tube voiding detection is possible at these temperatures. The results of all 20°C testing are summarized in Table 1.

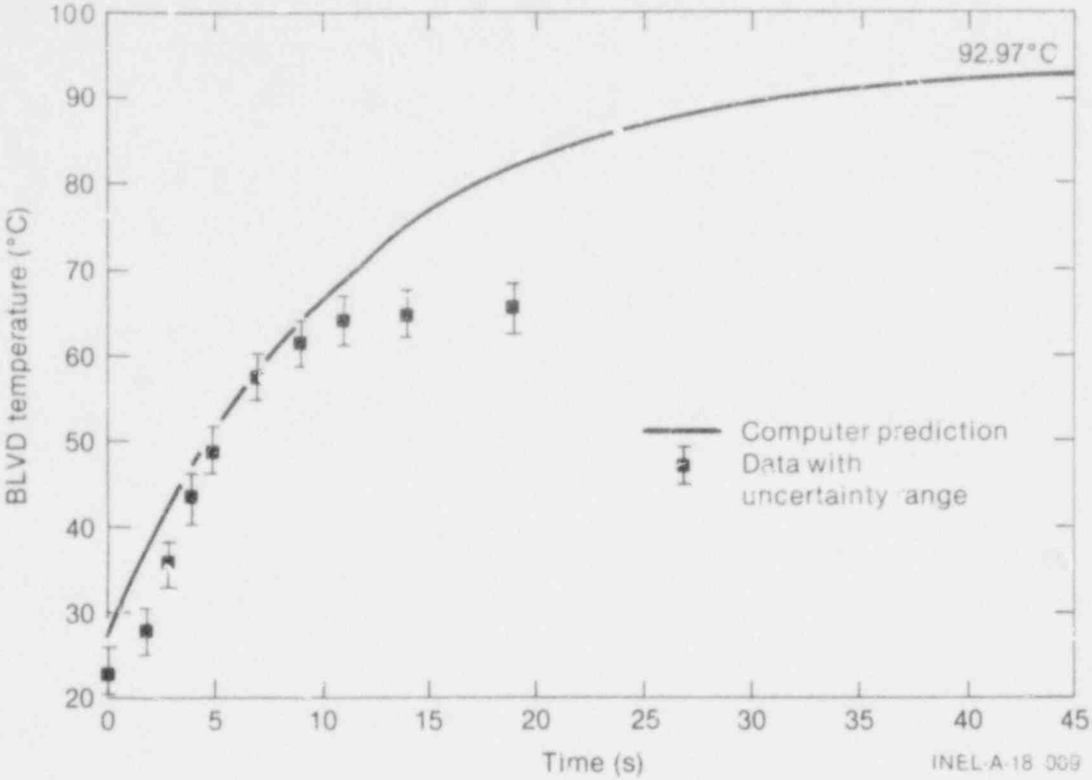

Figure 9. A comparison of the actual BLVD response to voiding with the transient computer model prediction at 16°C with 0.51 l/s initial flow.

Table 1. BLVD pump coastdown and voiding data near 20°C.

			Temperature (°C)				
Run	Flowrate (l/s)	Velocity (m/s)	Primary	Secondary	Initial Operating	Final Pump Off	Final Voided
1	0.50	2.34	18.2	14.7	22.7	64.1	69.9
2	0.50	2.34	N/A[a]	N/A	22.8	N/A	68.1
3	0.50	2.34	18.8	15.2	23.1	62.3	N/A
4	0.50	2.34	18.9	15.3	23.2	58.8	N/A
12	0.50	2.34	21.5	16.6	25.5	66.5	N/A

---

[a] Not available.

The BLVD's time constant associated with void detection could not be adequately determined. The observed response time of the device was considerably less than the originally calculated value. Thus the time required for air injection to void the U-tube was large compared to the total response time.

Other factors made determination of the BLVD's time constant difficult. It was not possible to ensure that all the water including water droplets had been removed when voiding occurred. In addition, the response to pump coastdown is imposed on the BLVD thermocouple output.

The system was brought to 80°C with a small temperature difference between the primary and secondary sides of the U-tubes. A series of pump coastdown tests were run (0.063, 0.13, 0.19, and 0.88 l/s). Figures 10 and 11 show results for the 0.063 and 0.88 l/s tests, respectively. The change in heater

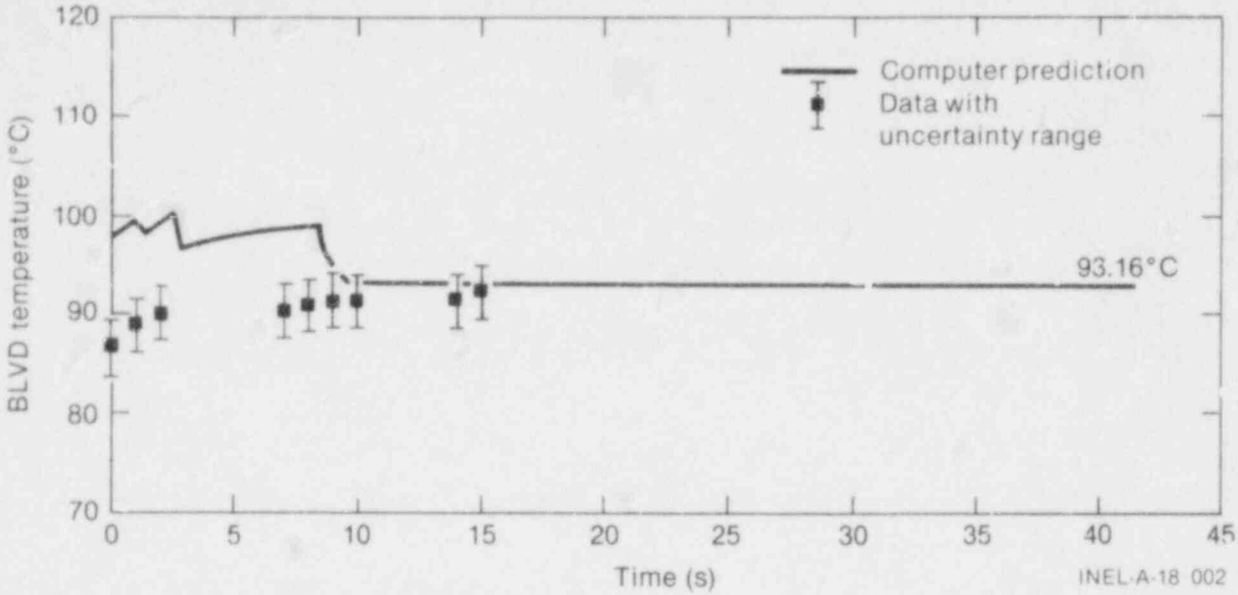

Figure 10. A comparison of the actual BLVD response to pump coastdown with the transient computer model prediction at 80°C with 0.063 l/s flow initial.

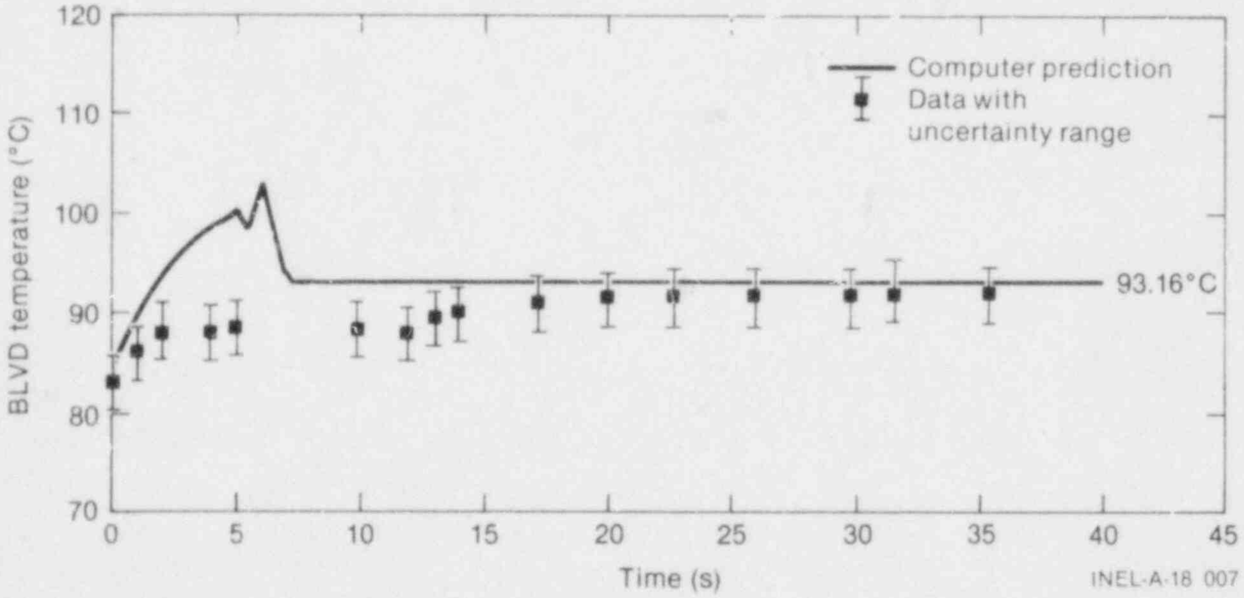

Figure 11. A comparison of the actual BLVD response to pump coastdown with the transient computer model prediction at 80°C with 0.88 l/s initial flow.

temperature due to pump coastdown is rather small. Air injection and pump coastdown produced identical final BLVD temperatures, hence no voiding discrimination. The heater power was increased to 130 W. A pump coastdown and U-tube voiding test was repeated. Voiding discrimination was still not possible. The test results at 80°C are summarized in Table 2.

The loss of voiding discrimination was attributed to subcooled nucleate boiling. Careful visual observation of the BLVD indicated the existence of boiling after pump coastdown or voiding.

An understanding of the insensitivity of BLVD's temperature to voiding and heater power can be obtained by reviewing the pool boiling curve in Figure 12. In the single phase region, the heat flux is in proportion to the temperature difference (T_w - T_f) to the 5/4 power. In the nucleate boiling region, this relationship becomes proportional to the third power. Transition to nucleate boiling makes it possible for the BLVD to dissipate the heater power without a measurable increase in temperature. The nucleate boiling heat transfer is so effective that an increase of the heater power to 130 W did not increase the BLVD temperature under voided conditions.

The lumped parameter model will not accurately describe the BLVD under boiling conditions. Large heat transfer coefficients associated with nucleate boiling produce a Biot modulus considerably greater than 0.1, thus making the lumped parameter model inappropriate.

Table 2 BLVD pump coastdown and voiding data near 80°C.

			Temperature (°C)				
Run	Flowrate (l/s)	Velocity (m/s)	Primary	Secondary	Initial Operating	Final Pump Off	Final Voided
5	0.063	0.29	77.5	79.0	86.9	92.8	N/A[a]
6	0.13	0.59	78.4	79.3	84.1	92.1	N/A
7	0.19	0.88	79.4	79.5	83.8	92.8	N/A
8	0.88	4.1	80.7	79.9	83.1	92.2	N/A
9	0.88	4.1	80.9	80.3	83.2	92.1	93.5
10[b]	0.88	4.1	80.8	82.1	90.2	N/A	93.0
11	0.063	0.29	81.0	82.3	90.5	92.4	92.6
13	0.50	2.34	62.1	61.8	64.9	93.2	N/A
14	0.13	0.59	62.2	63.2	68.0	92.9	N/A

---

[a] Not available.

[b] Heater power is 130 W.

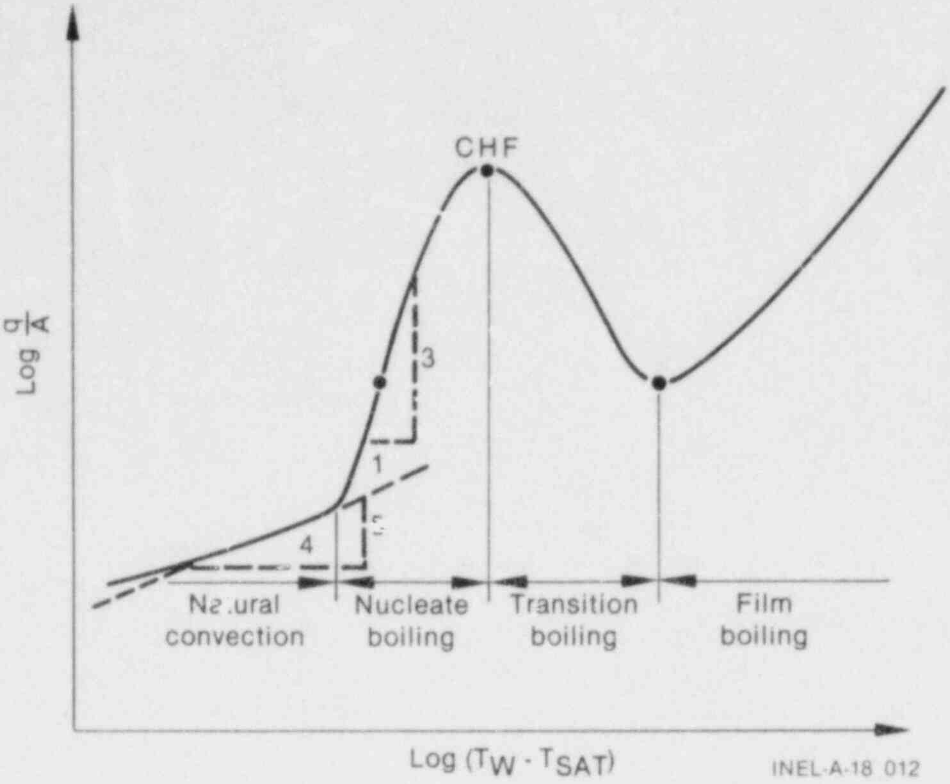

Figure 12. A typical pool boiling curve for water.

The temperatures on either side of the BLVD were measured to assess the axial conduction. Figures 13 and 14 compare typical but limited data with the one-dimensional relaxation calculation. There is reasonable agreement, especially when the simplicity of the computer model is considered.

The temperatures on the sides of the BLVD are reasonably close to the temperature of the ambient. Axial conduction effects are thus small and can be neglected.

Boiling was suppressed on the secondary side of the BLVD by wrapping glass tape around it. Data were acquired at 20°C and indicated an increased sensitivity to U-tube voiding. These tests were run at 1 and 8 gpm for a heater power of 80 W.

The system temperature was increased to 80°C, and additional data were acquired with the insulated BLVD. These results are summarized in Table 3. Pump coastdown was properly detected by the BLVD as well as voiding by air on the primary side. However, the heat addition of the BLVD now causes voiding on the primary side. The insulation of the secondary side produced higher temperatures in the BLVD and these temperatures now boil the primary fluid when it is not being circulated. This is an undesirable situation, since the void sensor is creating voiding at the point of measurement. Lower powers only reduce the time required for boiling as well as the sensitivity of the device.

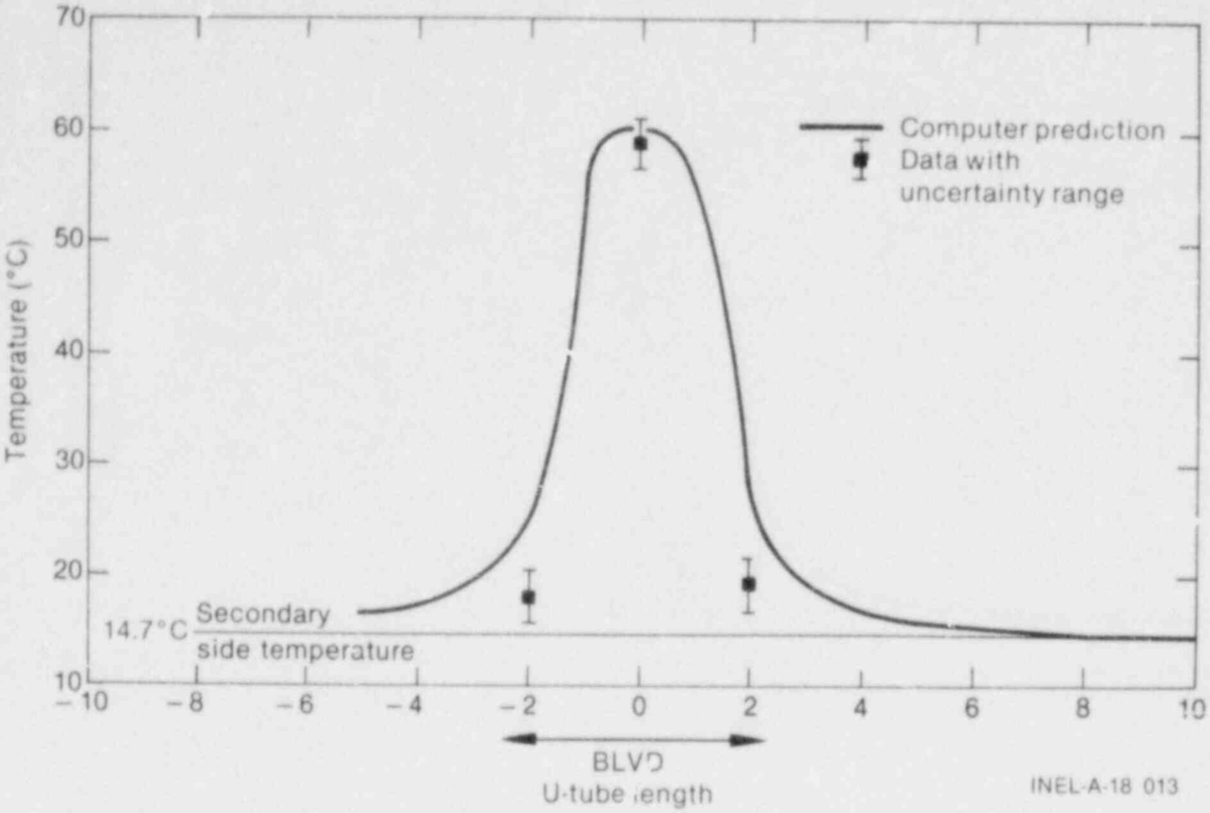

Figure 13. A comparison of the measured axial temperature distribution to a one-dimensional relaxation prediction for a water filled U-tube instrumented with a BLVD.

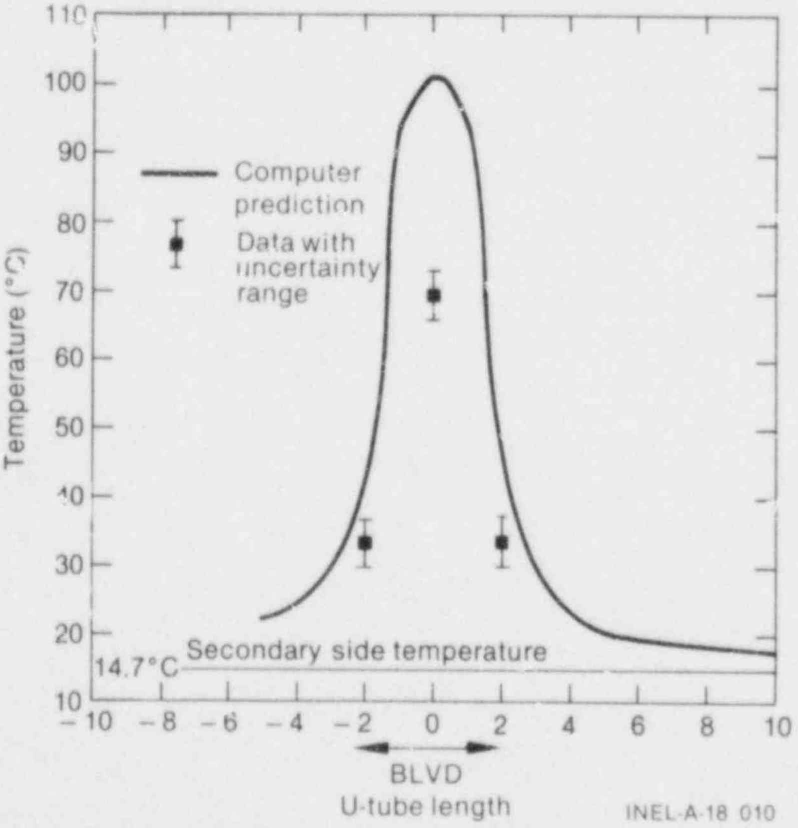

Figure 14. A comparison of the measured axial temperature distribution to a one-dimensional relaxation prediction for a voided U-tube instrumented with a BLVD.

Table 3. BLVD pump coastdown and voiding data with glass tape on the secondary side.

			Temperature (°C)				
Run	Flowrate (gpm)	Velocity (m/s)	Primary	Initial Secondary	Final Operating	Final Pump Off	Voided
15	0.50	2.34	20.2	14.9	24.2	93.3	N/A[a]
16	0.50	2.34	20.3	15.1	24.2	N/A	148.6
17	0.063	0.29	19.9	15.5	36.2	88.6	N/A
18	0.50	2.34	82.5	82.3	86.0	183.0[b]	N/A
19	0.50	2.34	83.0	82.9	86.4	171.6[b]	N/A
20	0.063	0.29	81.5	83.4	91.9	182.6[b]	N/A
21	0.19	0.88	84.1	84.4	89.5	182.4[b]	200.7

---

[a] Not available.

[b] Voiding on primary side.

ERROR ANALYSIS

Several sources of error are associated with the BLVD testing. These include:

1. The error in thermocouple reading due to differences in fabrication
2. The error in the thermocouple amplifier and data logger circuitry
3. The uncertainty associated with reading the BLVD thermocouple voltage from the strip chart recorder.

Error due to Type K thermocouple fabrication is usually about ±2.2°C or ±0.75% of reading whichever is greater[8] for a 0°C reference junction. This error is sufficiently small for this experiment. Accurate calibrations were performed to ensure that the thermocouple amplifiers, strip chart recorder, and data logger were functioning accurately.

The error associated with reading the thermocouple voltage from the strip chart recorder can be assessed using the technique described by Kline and McClintock.[9] The algorithm used to convert thermocouple voltage into temperature is

$$T_c = \frac{(33.7322395 + 44.2452975V_m - 0.2017185V_m^2 - 32.0)}{1.8} \tag{20}$$

where

T_c = temperature, °C

V_m = thermocouple output, mv.

Taking the derivative of Equation (20) with respect to voltage yields

$$\frac{\partial T_c}{\partial V_m} = 24.5807208 - 0.22413167V_m. \tag{21}$$

The error expression from Reference 9 is

$$\Delta T_c = \pm\sqrt{\left(\frac{\partial T_c}{\partial V_m}\right)^2 (\Delta V_m)^2}. \tag{22}$$

Substituting Equation (21) into (22) and noting that $\Delta V_m = 0.02$ mV yields the error as a function of the measured voltage[a]. Figure 15 illustrates the uncertainty in temperature caused by reading the temperature from the strip chart recorder. The maximum error associated with the voltage to temperature algorithm is ±0.5°C.

The total error associated with BLVD's temperature is the sum of the fabrication and voltage to temperature algorithm errors. Over the temperature range studied, this amounts to a maximum uncertainty of ±2.7°C.

---

[a] This value is based on the accuracy of reading the BLVD's thermocouple voltage from the strip chart recording.

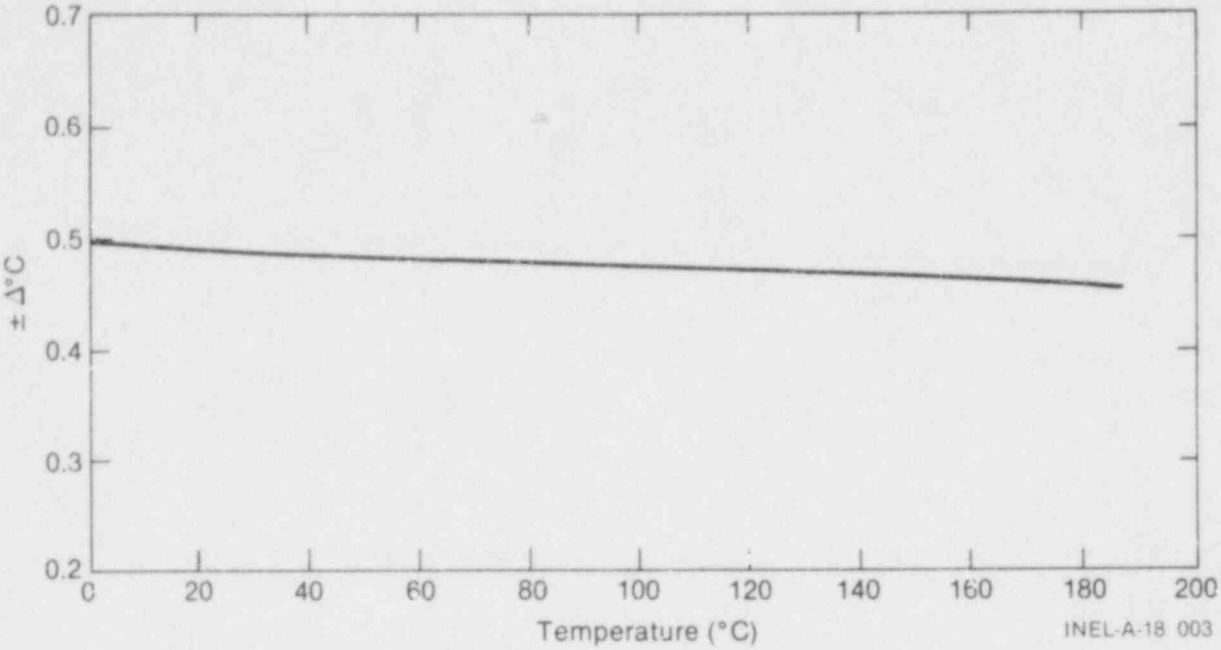

Figure 15. The uncertainty in BLVD temperature due to the voltage temperature algorithm.

SUMMARY AND CONCLUSIONS

A series of tests were performed to obtain the response time of the BLVD and to assess its response in nucleate boiling conditions. Two computer models were developed to calculate the steady state and transient response of the BLVD. The lumped parameter transient model was reasonably adequate at the lower temperatures but did not perform well at higher temperatures near fluid saturation. The one-dimensional steady state relaxation produced sufficient results in all temperature ranges.

Boiling was found to severely inhibit the response of the BLVD. The very effective heat transfer mechanism associated with boiling was able to hold the BLVD's temperature constant despite primary side voiding. Later tests, with the secondary side of the BLVD insulated, indicated that the additional heat input of the sensor was significant. In fact, this heat will cause boiling in a quiescent primary side fluid. The BLVD actually voids the U-tube and then will correctly indicate a voided tube.

Several conclusions can be drawn regarding BLVD performance and steam generator application:

1. A bare BLVD cannot detect U-tube voiding if boiling is present. Boiling would usually be present in a PWR steam generator.

2. In regions where boiling is not possible. (large subcoolings, liquid metals) the BLVD can operate as a voiding detector.

3. The BLVD's heater was observed to force the primary side into boiling, thus a pipe with liquid inside could be voided by the sensor. Insulation of the primary and secondary sides of the BLVD is possible, but the device's sensitivity would be reduced significantly. Microprocessor control of the BLVD's heater might also be used to prevent boiling, particularly on the primary side.

4. Lumped parameter models and one-dimensional relaxation codes are generally adequate for BLVD simulation. The large heat transfer coefficients associated with nucleate boiling violate a fundamental assumption for the lumped parameter model. Different techniques must then be used to simulate the BLVD under this condition.

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APPENDIX A

COMPUTER SIMULATION FOR LUMPED PARAMETER TRANSIENT BLVD MODEL

APPENDIX A

COMPUTER SIMULATION FOR LUMPED PARAMETER TRANSIENT BLVD MODEL

This appendix contains a listing of the computer program used to simulate the transient response of the BLVD. The code is based on a lumped parameter model and neglects any axial conduction. Common heat transfer coefficient correlations are also included.

The code is written in BASIC and designed to run on a Textronix 4052 computer. Execution and the necessary input/output usually requires about 45 s per case. The code will prompt the user for any necessary input. A typical output is also included.

```
100 PAGE
110 REM
120 REM          THIS PROGRAM SIMULATES THE TRANSIENT RESPONSE OF A
130 REM      BOUNDARY LAYER VOIDING DETECTOR FOR U-TUBE STEAM
140 REM      GENERATORS.  THE MODEL ASSUMES A LUMPED PARAMETER SYSTEM.
150 REM      HEAT TRANSFER IS CONSIDERED ON BOTH SIDES.  NATURAL
160 REM      CONVECTION IS ASSUMED ON THE SECONDARY SIDE WHILE FORCED
170 REM      OR NATURAL CONVECTION MAY BE APPLIED ON THE PRIMARY SIDE.
180 REM      THE DITTUS-BOELTER CORRELATION IS EMPLOYED AS THE FORCED
190 REM      CONVECTION RELATIONSHIP WHILE THE MCADAMS' CORRELATION IS
200 REM      USED FOR NATURAL CONVECTION.  AXIAL CONDUCTION IS
210 REM      NEGLECTED.  BOILING IS CONSIDERED ON EITHER SIDE.
220 REM      ROSENHOW'S CORRELATION FOR POOL BOILING IS EMPLOYED
230 REM      ON THE SECONDARY SIDE WHILE THE JENS AND LOTTES FLOW
240 REM      BOILING CORRELATION IS USED ON THE PRIMARY SIDE.  SUPER-
250 REM      POSITION OF THE SINGLE PHASE AND BOILING HEAT TRANSFER
260 REM      COEFFICIENT IS ASSUMED.  THE COMPUTER MODEL AUTOMATICALLY
270 REM      INCLUDES BOILING HEAT TRANSFER WHEN THE VOIDING DETECTOR
280 REM      TEMPERATURE EXCEEDS THE NUCLEATION TEMPERATURE.
290 REM
300 REM      WRITTEN BY MARK VINCE 7/17/80
310 REM      LATEST REVISION  8/12/80, 9/8/80
320 REM
330 REM
340 REM                VARIABLES
350 REM
360 REM      U1=TELETYPE INPUT/OUTPUT UNIT
370 REM      U2=LINEPRINTER
380 REM      U3=DATA INPUT UNIT, I.E. MAG TAPE
390 REM      T1=SECONDARY SIDE FLUID TEMPERATURE, F
400 REM      T2=PRIMARY SIDE FLUID TEMPERATURE, F
410 REM      T3=PRIMARY SIDE SATURATION TEMPERATURE, F
420 REM      T4=SECONDARY SIDE SATURATION TEMPERATURE, F
430 REM      M1=SECONDARY SIDE HEAT TRANSFER COEFFICIENT, WATTS/F
440 REM      A1=SECONDARY SIDE HEAT TRANSFER AREA, FT SQUARED
450 REM      N1=PRIMARY SIDE HEAT TRANSFER COEFFICIENT, WATTS/F
460 REM      A2=PRIMARY SIDE HEAT TRANSFER AREA, FT SQUARED
470 REM      M3=SECONDARY SIDE BOILING HEAT TRANSFER COEFFICIENT
480 REM      N3=PRIMARY SIDE BOILING HEAT TRANSFER COEFFICIENT
490 REM      H1=SECONDARY SIDE HEAT TRANSFER VARIABLE
500 REM      H2=PRIMARY SIDE HEAT TRANFER VARIABLE
510 REM      H3=SECONDARY SIDE BOILING HEAT TRANSFER VARIABLE
520 REM      H4=PRIMARY SIDE BOILING HEAT TRANSFER VARIABLE
530 REM      H9=HEAT OF VAPORIZATION, BTU/LBM
540 REM      H8=SURFACE TENSION, LBF / FT
550 REM      P9=PRIMARY SIDE PRESSURE, PSIA
560 REM      D1=TIME STEP INCREMENT
570 REM      V1=HEATER&PIPE VOLUME * DENSITY * SPECIFIC HEAT, SECONDS
580 REM      T(J)=TEMPERATURE AS A FUNCTION OF TIME, F
590 REM      T9(J)=TIME ARRAY
```

```
600 REM         P3,P4,P5=PRANDTL NUMBERS
610 REM         P(6,4)=PROPERTIES ARRAY FOR WATER, 304 SS, AIR, AND STEAM
620 REM         R1=REYNOLDS NUMBER
630 REM         K1 THROUGH K4= MISCELLANEOUS INTERNAL CONSTANTS
640 REM         K5 THROUGH K9= TEMPERATURE DIFFERENCES, F
650 REM         D2=PIPE OUTER DIAMETER, INCHES
660 REM         D3=PIPE WALL THICKNESS, INCHES
670 REM         D4=PIPE INNER DIAMETER, FEET
680 REM         D6=PIPE AND WIRE DIAMETER, FEET
690 REM         D8=CONVERGENCE CRITERIA TEMPERATURE DIFFERENCE, F
700 REM         Q2=WALL SUPERHEAT, F
710 REM         Z1=INTERNAL VARIABLE
720 REM         C1,C2=MISCELLANEOUS CONSTANTS
730 REM         C7,C8,C9=INTERNAL VARIABLES
740 REM         G1,G2,G3=INTERNAL VARIABLES
750 REM         G4,G5,G6=NUCLEATION TEMPERATURES, F
760 REM         F1,F2,B1=NUCLEATION FLAGS
770 REM         Y1=TIME OF NUCLEATION, SECONDS
780 REM         U5=VFG @ 14.696 PSIA
790 REM
800 DELETE T,T9,G
810 DIM T(200),T9(200),P(6,4),G(200)
820 REM
830 REM         INPUT/OUTPUT UNITS
840 REM
850 U1=32
860 U2=51
870 U3=33
880 REM         CONSTANTS
890 A$="WATERSTEELAIR  STEAM"
900 D9=0.04
910 C1=1
920 C2=1.25
930 Q2=1
940 Q9=0.1
950 REM
960 REM         PHYSICAL CONSTANTS @ 60  F
970 REM
980 B1=1054.8/3600
990 REM
1000 REM         DENSITY, LBM / CU FT
1010 P(1,1)=62.3
1320 P(1,2)=488
1030 P(1,3)=0.077
1040 P(1,4)=0.0372
1050 REM        SPECIFIC HEAT, BTU / LBM F
1060 P(2,1)=0.999
1070 P(2,2)=0.11
1080 P(2,3)=0.24
1090 P(2,4)=0.451
1100 REM        DYNAMIC VISCOSITY, LBM / FT SEC
1110 P(3,1)=7.6E-4
1120 P(3,2)=0
1130 P(3,3)=1.214E-5
1140 P(3,4)=8.7E-6
1150 REM        KINEMATIC VISCOSITY, FT SQ / SEC
1160 P(4,1)=1.22E-5
1170 P(4,2)=0
1180 P(4,3)=1.59E-4
1190 P(4,4)=2.34E-4
1200 REM        THERMAL CONDUCTIVITY, BTU / HR FT F
1210 P(5,1)=0.34
1220 P(5,2)=9.19
1230 P(5,3)=0.0146
1240 P(5,4)=0.0145
1250 REM        GRASHOF CONSTANT, 1 / F CU FT
1260 P(6,1)=1.84E+7
1270 P(6,2)=0
1280 P(6,3)=2584000
1290 P(6,4)=877000
```

```
1300 REM        HEAT OF VAPORIZATION, BTU / LBM @ 14.696 PSIA
1310 H9=970.3
1320 REM        SURFACE TENSION, LBF / FT
1330 H8=0.0041
1340 REM        VFG , CU FT / LBM @ 14.696 PSIA
1350 V5=26.782
1360 REM
1370 REM        SET INITIAL CONDITIONS
1380 REM
1390 PRINT @U1:"ENTER INITIAL PRIMARY SIDE FLUID CODE            ";
1400 INPUT S1
1410 PRINT @U1:"ENTER FINAL PRIMARY SIDE FLUID CODE              ";
1420 INPUT S2
1430 PRINT @U1:"ENTER SECONDARY SIDE FLUID CODE                  ";
1440 INPUT S3
1450 REM
1460 PRINT @U2: USING "P":
1470 PRINT @U2:"THIS MODEL CALCULATES THE THERMAL TRANSIENT EXPERIENCED"
1480 PRINT @U2:"BY A BOUNDARY LAYER FLOW METER."
1490 D$=SEG(A$,(S1-1)*5+1,5)
1500 PRINT @U2: USING 1510:D$," IS INITIALLY ON THE PRIMARY SIDE"
1510 IMAGE L,5A,1X,33A
1520 D$=SEG(A$,(S2-1)*5+1,5)
1530 PRINT @U2: USING 1540:"THIS FLUID IS REPLACED BY ",D$
1540 IMAGE L,26A,1X,5A
1550 D$=SEG(A$,(S3-1)*5+1,5)
1560 PRINT @U2: USING 1570:D$," IS THE SECONDARY SIDE FLUID"
1570 IMAGE L,5A,1X,28A
1580 PRINT @U1:"ENTER OUTER PIPE DIAMETER, INCHES                ";
1590 INPUT D2
1600 PRINT @U1:"ENTER PIPE WALL THICKNESS, INCHES                ";
1610 INPUT D3
1620 PRINT @U2: USING 1630:"PIPE OUTER DIAMETER = ",D2," INCHES"
1630 IMAGE L,22A,2D.3D,7A
1640 PRINT @U2: USING 1650:"PIPE WALL THICKNESS = ",D3," INCHES"
1650 IMAGE L,22A,2D.4D,7A
1660 REM
1670 REM        PIPE DIMENSION CALCULATIONS
1680 D2=D2/12
1690 D3=D3/12
1700 D4=D2-2*D3
1710 D5=1/(16*12)
1720 D6=D2+2*D5
1730 D7=0.75
1740 REM
1750 REM        SET TIME STEP
1760 REM
1770 PRINT @U1:"ENTER TIME STEP, SECONDS                         ";
1780 INPUT D1
1790 REM
1800 REM        TEMPERATURES
1810 REM
1820 PRINT @U1:"ENTER PRIMARY SIDE TEMPERATURE, F                ";
1830 INPUT T2
1840 PRINT @U2: USING 1850:"PRIMARY SIDE TEMPERATURE = ",T2," F"
1850 IMAGE L,27A,3D.2D,2A
1860 PRINT @U1:"ENTER SECONDARY SIDE TEMPERATURE, F              ";
1870 INPUT T1
1880 PRINT @U2: USING 1890:"SECONDARY SIDE TEMPERATURE = ",T1," F"
1890 IMAGE L,29A,3D.2D,2A
1900 PRINT @U1:"ENTER PRIMARY SIDE SATURATION TEMPERATURE, F     ";
1910 INPUT T3
1920 PRINT @U2: USING 1930:"PRIMARY SIDE SATURATION TEMPERATURE = ",T3
1930 IMAGE L,38A,3D.2D
1940 PRINT @U1:"ENTER SECONDARY SIDE SATURATION TEMPERATURE, F ";
1950 INPUT T4
1960 PRINT @U2: USING 1970:"SECONDARY SIDE SATURATION TEMPERATURE = ",T4
1970 IMAGE L,40A,3D.2D
1980 PRINT @U1:"ENTER PRIMARY SIDE PRESSURE, PSIA                ";
```

```
1990 INPUT P9
2000 PRINT @U2: USING 2010:"PRIMARY SIDE PRESSURE = ",P9," PSIA"
2010 IMAGE L,24A,4D.2D,5A
2020 PRINT @U1:"ENTER PRIMARY SIDE WATER VELOCITY, FT./SECOND   ";
2030 INPUT J1
2040 PRINT @U2: USING 2050:"PRIMARY SIDE WATER VELOCITY = ",J1," FT/SEC"
2050 IMAGE L,30A,2D.3D,7A
2060 PRINT @U1:"ENTER HEATER POWER, WATTS                         ";
2070 INPUT P1
2080 PRINT @U2: USING 2090:"HEATER POWER = ",P1," WATTS"
2090 IMAGE L,15A,4D.1D,6A
2100 REM
2110 REM       CALCULATE REYNOLDS NUMBER AND FLAG LAMINAR FLOW CASE
2120 REM
2130 R1=J1*D4/P(4,S1)
2140 PRINT @U2: USING 2150:"PRIMARY SIDE REYNOLDS NUMBER = ",R1
2150 IMAGE L,31A,8D.1D,L
2160 IF R1<2100 THEN 2180
2170 GO TO 2230
2180 PRINT @U2:"******* LAMINAR FLOW PRESENT *******"
2190 REM
2200 REM         SINGLE PHASE HEAT TRANSFER COEFFICIENTS
2210 REM
2220 REM         SECONDARY, NATURAL CONVECTION
2230 P3=P(2,S3)*P(3,S3)/P(5,S3)*3600
2240 M1=0.53*B1*(P(5,S3)/D6)*(P(6,S3)*D6↑3*P3)↑0.25
2250 A1=D7/12*PI*D6
2260 M1=M1*A1
2270 REM         PRIMARY, NATURAL CONVECTION
2280 P4=P(2,S2)*P(3,S2)/P(5,S2)*3600
2290 N1=0.53*B1*(P(5,S2)/D4)*(P(6,S2)*D4↑3*P4)↑0.25
2300 A2=D7/12*PI*D4
2310 N1=N1*A2
2320 REM         PRIMARY, FORCED CONVECTION
2330 P5=P(2,S1)*P(3,S1)/P(5,S1)*3600
2340 N2=0.023*(P(5,S1)/D4)*R1↑0.8*P5↑0.4*A2*B1
2350 REM
2760 V2=PI*(D7/12)*(D6↑2-D4↑2)*(1054.8/4)
2370 V1=V2*P(1,2)*P(2,2)
2380 REM
2390 REM         BOILING HEAT TRANSFER COEFFICIENTS
2400 REM
2410 REM         SECONDARY, POOL BOILING
2420 Z8=P(3,1)*H9/(H8/(P(1,1)-P(1,4)))↑0.5
2430 Z9=(P(2,1)/(H9*P3↑1.7*0.0133))↑3
2440 M3=Z8*Z9*A1*1054.8
2450 REM         PRIMARY, SUBCOOLED BOILING
2460 Z7=(EXP(P9/900)/60)↑4
2470 N3=Z7*A2*B1*1000000
2480 REM         CALCULATE PRIMARY SIDE NUCLEATION CRITERIA
2490 REM
2500 W8=B1*P(5,S1)/(8*H8*T3*V5/(778*H9))
2510 G1=-(2*T3+N2/A2/W8)
2520 G2=T2*(N2/A2)/W8+T3↑2
2530 G3=(G1↑2-4*G2)↑0.5
2540 G6=(-G1+G3)/2
2550 REM
2560 REM         CALCULATE OPERATING TEMPERATURE PRIOR TO TRANSIENT
2570 REM         FOR ZERO LIQUID FLOW
2580 REM
2590 IF R1>2100 THEN 2630
2600 C1=1.25
2610 N2=0.53*B1*A2*(P(5,S1)/D4)*(P(6,S1)*D4↑3*P5)↑0.25
2620 REM
2630 T6=(T1+T2)/2
2640 T(1)=(P1/(M1+N2))↑0.8+T6
2650 REM
2660 FOR J=1 TO 100
2670 Z1=P1-N2*(T(1)-T2)↑C1-M1*(T(1)-T1)↑C2
```

```
2680 REM
2690 IF ABS(Z1)<0.1 THEN 2740
2700 REM          INCREMENT TEMPERATURE
2710 T(1)=T(1)+Q9*Z1
2720 NEXT J
2730 REM
2740 IF P1<2100 THEN 3160
2750 REM
2760 REM        CALCULATE SECONDARY SIDE NUCLEATION CRITERIA
2770 W8=B1*P(5,S3)/(8*H8*T4*V5/(778*H9))
2780 G1=-(2*T4+M1*(T(1)-T1)↑0.25/A1/W8)
2790 G2=T1*M1*(T(1)-T1)↑0.25/A1/W8+T4↑2
2800 G3=(G1↑2-4*G2)↑0.5
2810 G4=(-G1+G3)/2
2820 H3=0
2830 H4=0
2840 REM          LOOP TO FIND LIQUID FLOW OPERATING TEMPERATURE USING
2850 REM          NON-ZERO LIQUID FLOW CASE TEMPERATURE AS FIRST GUESS
2860 REM
2870 FOR J=1 TO 100
2880 REM          CHECK FOR NUCLEATION ON SECONDARY SIDE
2890 IF T(1)<G4 THEN 2940
2900 PRINT @U2:"SECONDARY SIDE BOILING"
2910 Q9=0.01
2920 H3=M3*(T(1)-T4)↑2
2930 REM          CHECK FOR PRIMARY SIDE NUCLEATION
2940 IF T(1)<G6 THEN 2980
2950 PRINT @U2:"PRIMARY SIDE BOILING"
2960 H4=N3*(T(1)-T3)↑4
2970 REM
2980 Z1=P1-(M1*(T(1)-T1)↑C2+H3)-(N2*(T(1)-T2)+H4)
2990 IF ABS(Z1)<0.1 THEN 3160
3000 T8=T(1)
3010 REM          INCREMENT TEMPERATURE
3020 REM
3030 T(1)=T(1)+Q9*Z1
3040 REM
3050 REM        PROVIDE DAMPING TO AVOID LARGE TEMPERATURE OSCILLATIONS
3060 REM
3070 D7=D9*T(1)
3080 D8=ABS(T(1)-T8)
3090 REM IF D8>D7 THEN 3100
3100 GO TO 3130
3110 T(1)=T(1)-D7
3120 PRINT @U2:"**** TEMPERATURE ARTIFICIALLY DAMPED ****"
3130 NEXT J
3140 PRINT @U2:"******  INITIAL TEMPERATURE SEARCH NOT CONVERGED  *****"
3150 REM          INITIALIZE TIME
3160 T9(1)=0
3170 G(1)=(T(1)-32)/1.8
3180 REM          RECALCULATE SECONDARY SIDE NUCLEATION CRITERION
3190 REM
3200 W8=B1*P(5,S3)/(8*H8*T4*V5/(778*H9))
3210 G1=-(2*T4+M1*(T(1)-T1)↑0.25/A1/W8)
3220 G2=T1*M1*(T(1)-T1)↑0.25/A1/W8+T4↑2
3230 G3=(G1↑2-4*G2)↑0.5
3240 G4=(-G1+G3)/2
3250 REM          RECALCULATE PRIMARY SIDE NUCLEATION CRITERIA
3260 W8=B1*P(5,S2)/(8*H8*T3*V5/(778*H9))
3270 G1=-(2*T3+N1/A2/W8)
3280 G2=T2*(N1/A2)/W8+T3↑2
3290 G3=(G1↑2-4*G2)↑0.5
3300 G5=(-G1+G3)/2
3310 REM
3320 REM          PRINT HEADER
3330 REM
3340 PRINT @U2: USING 3350:" TIME     TEMPERATURE"
3350 IMAGE L,21A
3360 PRINT @U2:"SECONDS         F"
```

```
3370 PRINT @U2: USING 4010:T9(1),T(1),G(1)
3380 REM
3390 REM          INITIALIZE TIME AND CONSTANTS
3400 REM
3410 T9(2)=D1
3420 F1=0
3430 H3=0
3440 REM
3450 REM          LOOP THROUGH TIME
3460 REM
3470 FOR J=2 TO 200
3480 REM
3490 REM          SET TEMPERATURE DIFFERENCES
3500 REM
3510 K9=T(J-1)-T1
3520 K8=T(J-1)-T2
3530 Q2=T(J-1)-G4
3540 K5=T(J-1)-T4
3550 REM
3560 C9=ABS(K9)
3570 C8=ABS(K8)
3580 K7=C9↑0.25
3590 K6=C8↑0.25
3600 REM
3610 REM          CHECK AND ALLOW FOR NEGATIVE TEMPERATURE DIFFERENCES
3620 REM
3630 IF K9=C9 THEN 3650
3640 K7=-K7
3650 IF K8=C8 THEN 3700
3660 K6=-K6
3670 REM
3680 REM          CALCULATE ACTUAL HEAT TRANSFER COEFFICIENTS
3690 REM          NON-BOILING CALCULATION
3700 H1=M1*K7
3710 H2=N1*K6
3720 IF Q2<0 THEN 3790
3730 REM          BOILING CALCULATION, SECONDARY SIDE ONLY
3740 F1=1
3750 H3=M3*K5↑3
3760 REM
3770 REM          EVALUATE TEMPERATURE RESPONSE
3780 REM
3790 K1=H1*(T(1)-T1)+H3+H2*(T(1)-T2)-P1
3800 K2=H1+H3+H2
3810 K3=EXP(-(K2*T9(J))/V1)
3820 K4=(P1+(H1+H3)*T1+H2*T2)/K2
3830 REM
3840 REM          COMPUTE TEMPERATURE
3850 REM
3860 T(J)=K1*K3/K2+K4
3870 REM
3880 REM         PROVIDE DAMPING TO AVOID LARGE TEMPERATURE OSCILLATIONS
3890 REM
3900 D7=D9*T(J-1)
3910 D8=ABS(T(J)-T(J-1))
3920 REM IF D8>D7 THEN 3940
3930 GO TO 3990
3940 T(J)=T(J-1)-D7
3950 PRINT @U2:"*** TEMPERATURE ARTIFICIALLY DAMPED ***"
3960 REM
3970 REM        PRINT ANSWER AND INCREMENT TIME
3980 REM
3990 G(J)=(T(J)-32)/1.8
4000 PRINT @U2: USING 4010:T9(J),T(J),G(J)
4010 IMAGE 3D.2D,5X,4D.2D,5X,4D.2D
4020 REM
4030 REM CHECK APPROACH TO STEADY STATE
4040 REM
4050 T9(J+1)=T9(J)+D1
```

```
4060 IF F1<>1 THEN 4090
4070 IF T(J)>T4 THEN 4090
4080 T(J)=T4
4090 IF D8<0.1 THEN 4110
4100 NEXT J
4110 PRINT @U1:"WOULD YOU LIKE TO RUN ANOTHER CASE ? ";
4120 INPUT Z9
4130 IF Z9>0 THEN 1280
4140 END
```

```
THIS MODEL CALCULATES THE THERMAL TRANSIENT EXPERIENCED
BY A BOUNDARY LAYER FLOW METER.

WATER  IS INITIALLY ON THE PRIMARY SIDE

THIS FLUID IS REPLACED BY  WATER

WATER  IS THE SECONDARY SIDE FLUID

PIPE OUTER DIAMETER =  0.750 INCHES

PIPE WALL THICKNESS =  0.0490 INCHES

PRIMARY SIDE TEMPERATURE =  70.65 F

SECONDARY SIDE TEMPERATURE =  61.88 F

PRIMARY SIDE SATURATION TEMPERATURE = 208.00

SECONDARY SIDE SATURATION TEMPERATURE = 208.00

PRIMARY SIDE PRESSURE =   14.70 PSIA

PRIMARY SIDE WATER VELOCITY =  7.690 FT/SEC

HEATER POWER =   80.3 WATTS

PRIMARY SIDE REYNOLDS NUMBER =    34247.8


 TIME      TEMPERATURE
SECONDS        °F           °C
  0.00        86.87        30.48
  0.50        91.86        33.25
  1.00        96.49        35.83
  1.50       100.79        38.22
  2.00       104.79        40.44
  2.50       108.49        42.49
  3.00       111.92        44.40
  3.50       115.10        46.17
  4.00       118.05        47.80
  4.50       120.77        49.32
  5.00       123.30        50.72
  5.50       125.64        52.02
  6.00       127.81        53.23
  6.50       129.81        54.34
  7.00       131.67        55.37
  7.50       133.39        56.33
  8.00       134.99        57.22
  8.50       136.47        58.04
  9.00       137.84        58.80
  9.50       139.11        59.51
 10.00       140.29        60.16
 10.50       141.38        60.77
 11.00       142.39        61.33
```

11.50	143.34	61.85
12.00	144.21	62.34
12.50	145.02	62.79
13.00	145.77	63.21
13.50	146.47	63.60
14.00	147.12	63.96
14.50	147.72	64.29
15.00	148.28	64.60
15.50	148.81	64.89
16.00	149.29	65.16
16.50	149.74	65.41
17.00	150.16	65.65
17.50	150.55	65.86
18.00	150.91	66.06
18.50	151.25	66.25
19.00	151.57	66.43
19.50	151.86	66.59
20.00	152.13	66.74
20.50	152.39	66.88
21.00	152.62	67.01
21.50	152.84	67.14
22.00	153.05	67.25
22.50	153.24	67.36
23.00	153.42	67.45
23.50	153.58	67.55
24.00	153.74	67.63
24.50	153.88	67.71
25.00	154.02	67.79
25.50	154.14	67.86
26.00	154.26	67.92
26.50	154.37	67.98
27.00	154.47	68.04
27.50	154.57	68.09

APPENDIX B

COMPUTER SIMULATION OF THE BLVD USING A RELAXATION MODEL

APPENDIX B

COMPUTER SIMULATION OF THE BLVD USING A RELAXATION MODEL

This appendix contains a listing of the computer program used to simulate the steady state temperature in a steam generator U-tube containing a BLVD. The code consists of a series of one-dimensional equations. These equations consider convective as well as conductive heat transfer. Common heat transfer coefficient correlations are also included.

The code is written in BASIC and designed to run on a Textronix 4052 computer. Execution as well as the necessary input/output depend on the initial temperature distribution guess, the number of nodes used, and the convergence criterion selected. The code will prompt the user for any necessary input. A typical output is also included.

```
100 PAGE
110 REM
120 REM          THIS PROGRAM IS A ONE-DIMENSIONAL NODAL MODEL
130 REM          WHICH IS USED TO CALCULATE THE TEMPERATURE
140 REM          DISTRIBUTION IN A STRIP.  AXIAL CONDUCTION IS
150 REM          CONSIDERED.  HEAT CONVECTION IS CONSIDERED ON TWO SIDES
160 REM          BUT EMPLOYED AS SINGLE COEFFICIENT.  NATURAL CONVECTION
170 REM          IS ASSUMED ON THE SECONDARY SIDE WHILE FORCED
180 REM          OR NATURAL CONVECTION MAY BE APPLIED ON THE
190 REM          PRIMARY SIDE.  THE DITTUS-BOELTER CORRELATION IS
200 REM          EMPLOYED AS THE FORCED CONVECTION RELATIONSHIP WHILE
210 REM          THE MCADAMS' CORRELATION IS USED FOR NATURAL CONVECTION.
220 REM          BOILING CAN BE CONSIDERED.
230 REM          ROSENHOW'S CORRELATION FOR POOL BOILING IS EMPLOYED
240 REM          ON THE SECONDARY SIDE WHILE THE JENS AND LOTTES
250 REM          FLOW BOILING CORRELATION IS USED ON THE PRIMARY
260 REM          SIDE.  THE COMPUTER MODEL WILL ADJUST THE
270 REM          HEAT TRANSFER CORRELATION IF THE WALL TEMPERATURE
280 REM          EXCEEDS THE SATURATION TEMPERATURE.
290 REM
300 REM          WRITTEN BY MARK VINCE 8/26/80
310 REM          LATEST REVISION  8/26/80
320 REM
330 REM
340 REM                      VARIABLES
350 REM
360 REM          U1=TELETYPE INPUT/OUTPUT UNIT
370 REM          U2=LINEPRINTER
380 REM          U3=DATA INPUT UNIT, I.E. MAG TAPE
390 REM          T1=SECONDARY SIDE FLUID TEMPERATURE, F
400 REM          T2=PRIMARY SIDE FLUID TEMPERATURE, F
410 REM          T3=PRIMARY SIDE SATURATION TEMPERATURE, F
420 REM          T4=SECONDARY SIDE SATURATION TEMPERATURE, F
430 REM          T5(M)=SECONDARY SIDE TEMPERATURE DISTRIBUTION, F
440 REM          M1=SECONDARY SIDE HEAT TRANSFER COEFFICIENT, WATTS/F
450 REM          A1=SECONDARY SIDE HEAT TRANSFER AREA, FT SQUARED
460 REM          N1=PRIMARY SIDE HEAT TRANSFER COEFFICIENT, WATTS/F
470 REM          A2=PRIMARY SIDE HEAT TRANSFER AREA, FT SQUARED
480 REM          M3=SECONDARY SIDE BOILING HEAT TRANSFER COEFFICIENT
490 REM          N3=PRIMARY SIDE BOILING HEAT TRANSFER COEFFICIENT
500 REM          H1(M)=SECONDARY SIDE HEAT TRANSFER VARIABLE
510 REM          H2(M)=PRIMARY SIDE HEAT TRANFER VARIABLE
520 REM          H9=HEAT OF VAPORIZATION, BTU/LBM
530 REM          H8=SURFACE TENSION, LBF / FT
540 REM          P9=PRIMARY SIDE PRESSURE, PSIA
550 REM          P3,P4=PRANDTL NUMBERS
560 REM          P(6,4)=PROPERTIES ARRAY FOR WATER, 304 SS, AIR, AND STEAM
```

```
570 REM          R1=REYNOLDS NUMBER
580 REM          Z7 THROUGH Z9 = MISCELLANEOUS INTERNAL CONSTANTS
590 REM          D1=PIPE OUTER DIAMETER, INCHES
600 REM          D2=PIPE INNER DIAMETER, FEET
610 REM          D3=PIPE WALL THICKNESS, INCHES
620 REM          D5=PIPE AND WIRE DIAMETER, FEET
630 REM          Z1=INTERNAL VARIABLE
640 REM          C7,C8,C9=INTERNAL VARIABLES
650 REM          Q(N)=RESIDUALS
660 REM          W1(N)=CONSTANTS FOR EQUATIONS
670 REM          X1=HORIZIONTAL NODE SPACING, INCHES
680 REM          T(N)=TEMPERATURE AT EACH NODE, F
690 REM
700 O=16
710 DELETE Q,T,P,W1,T5,H1,H2,G
720 DIM T(O),W1(O),P(6,4),Q(O),T5(O),H1(O),H2(O),G(O)
730 REM
740 REM          INPUT/OUTPUT UNITS
750 REM
760 U1=32
770 U2=51
780 U3=33
790 REM
800 REM
810 REM
820 REM          PHYSICAL CONSTANTS @  60 F
830 REM
840 B1=1054.8/3600
850 REM
860 REM          DENSITY, LBM / CU FT
870 P(1,1)=62.3
880 P(1,2)=488
890 P(1,3)=0.077
900 P(1,4)=0.0372
910 REM        SPECIFIC HEAT, BTU / LBM F
920 P(2,1)=0.999
930 P(2,2)=0.11
940 P(2,3)=0.24
950 P(2,4)=0.451
960 REM        DYNAMIC VISCOSITY, LBM / FT SEC
970 P(3,1)=7.6E-4
980 P(3,2)=0
990 P(3,3)=1.214E-5
1000 P(3,4)=8.7E-6
1010 REM        KINEMATIC VISCOSITY, FT SQ / SEC
1020 P(4,1)=1.22E-5
1030 P(4,2)=0
1040 P(4,3)=1.59E-4
1050 P(4,4)=2.34E-4
1060 REM        THERMAL CONDUCTIVITY, BTU / HR FT F
1070 P(5,1)=0.34
1080 P(5,2)=9.19
1090 P(5,3)=0.0146
1100 P(5,4)=0.0145
1110 REM        GRASHOF CONSTANT, 1 / F CU FT
1120 P(6,1)=1.84E+7
1130 P(6,2)=0
1140 P(6,3)=2584000
1150 P(6,4)=877000
1160 REM         HEAT OF VAPORIZATION, BTU / LBM
1170 H9=987.15
1180 REM         SURFACE TENSION, LBF / FT
1190 H8=0.0041
1200 REM
1210 REM         SET INITIAL CONDITIONS
1220 REM
1230 PRINT @U1:"ENTER PRIMARY SIDE FLUID CODE                     ";
1240 INPUT S2
1250 PRINT @U1:"ENTER SECONDARY SIDE FLUID CODE                   ";
```

```
1260 INPUT S3
1270 REM
1280 PRINT @U2: USING "P":
1290 PRINT @U2:"THIS NODAL MODEL CALCULATES THE STEADY STATE "
1300 PRINT @U2:"TEMPERATURES ALONG THE SURFACE OF A BOUNDARY "
1310 PRINT @U2: LAYER FLOW METER."
1320 PRINT @U2: USING 1330:S2," IS ON THE PRIMARY SIDE"
1330 IMAGE L,2D,23A
1340 PRINT @U2: USING 1350:S3," IS THE SECONDARY SIDE FLUID"
1350 IMAGE L,2D,28A
1360 PRINT @U1:"ENTER OUTER PIPE DIAMETER, INCHES                    ";
1370 INPUT D1
1380 PRINT @U1:"ENTER PIPE WALL THICKNESS, INCHES                    ";
1390 INPUT D3
1400 PRINT @U2: USING 1410:"PIPE OUTER DIAMETER = ",D1," INCHES"
1410 IMAGE L,22A,2D.3D,7A
1420 PRINT @U2: USING 1430:"PIPE WALL THICKNESS = ",D3," INCHES"
1430 IMAGE L,22A,2D.4D,7A
1440 REM
1450 REM       CONVERT DIMENSIONS TO FEET AND CALCULATE PIPE ID
1460 REM
1470 D1=D1/12
1480 D3=D3/12
1490 D2=D1-2*D3
1500 D4=1/(16*12)
1510 D5=D1+2*D4
1520 REM
1530 REM        TEMPERATURES
1540 REM
1550 PRINT @U1:"ENTER PRIMARY SIDE TEMPERATURE, F                    ";
1560 INPUT T2
1570 PRINT @U2: USING 1580:"PRIMARY SIDE TEMPERATURE = ",T2," F"
1580 IMAGE L,27A,3D.2D,2A
1590 PRINT @U1:"ENTER SECONDARY SIDE TEMPERATURE, F                  ";
1600 INPUT T1
1610 PRINT @U2: USING 1620:"SECONDARY SIDE TEMPERATURE = ",T1," F"
1620 IMAGE L,29A,3D.2D,2A
1630 PRINT @U1:"ENTER PRIMARY SIDE SATURATION TEMPERATURE, F   ";
1640 INPUT T3
1650 PRINT @U2: USING 1660:"PRIMARY SIDE SATURATION TEMPERATURE = ",T3
1660 IMAGE L,38A,3D.2D
1670 PRINT @U1:"ENTER SECONDARY SIDE SATURATION TEMPERATURE, F ";
1680 INPUT T4
1690 PRINT @U2: USING 1700:"SECONDARY SIDE SATURATION TEMPERATURE = ",T4
1700 IMAGE L,40A,3D.2D
1710 PRINT @U1:"ENTER PRIMARY SIDE PRESSURE, PSIA                    ";
1720 INPUT P9
1730 PRINT @U2: USING 1740:"PRIMARY SIDE PRESSURE = ",P9," PSIA"
1740 IMAGE L,24A,4D.2D,5A
1750 PRINT @U1:"ENTER PRIMARY SIDE WATER VELOCITY, FT./SECOND  ";
1760 INPUT J1
1770 PRINT @U2: USING 1780:"PRIMARY SIDE WATER VELOCITY = ",J1," FT/SEC"
1780 IMAGE L.30A,2D.3D,7A
1790 PRINT @U1:"ENTER HEATER POWER, WATTS                            ";
1800 INPUT P1
1810 PRINT @U2: USING 1820:"HEATER POWER = ",P1," WATTS"
1820 IMAGE L.15A,3D.1D,6A
1830 PRINT @U1:"ENTER NUMBER OF NODES                                ";
1840 INPUT N
1850 PRINT @U1:"ENTER NODE SPACING, INCHES                           ";
1860 INPUT X1
1870 PRINT @U2: USING 1880:N," NODES SPACED ",X1," INCHES APART"
1880 IMAGE L,2D,14A.2D.3D,13A
1890 X1=X1/12
1900 REM
1910 REM      CALCULATE REYNOLDS NUMBER AND FLAG LAMINAR FLOW CASE
1920 REM
1930 R1=J1*D2/P(4,S2)
1940 PRINT @U2: USING 1950:"PRIMARY SIDE REYNOLDS NUMBER = ",R1
```

```
1950 IMAGE L,31A,8D.1D,L
1960 IF R1<2100 THEN 1980
1970 GO TO 2030
1980 PRINT @U2:"******* LAMINAR FLOW PRESENT *******"
1990 REM
2000 REM          HEAT TRANSFER COEFFICIENTS
2010 REM
2020 REM        OUTSIDE
2030 P3=P(2,S3)*P(3,S3)/P(5,S3)*3600
2040 M1=0.53*B1*(P(5,S3)/D5)*(P(6,S3)*D5↑3*P3)↑0.25
2050 A1=X1*PI*D5
2060 M1=M1*A1
2070 REM         INSIDE
2080 P4=P(2,S2)*P(3,S2)/P(5,S2)*3600
2090 N1=0.53*B1*(P(5,S2)/D2)*(P(6,S2)*D2↑3*P4)↑0.25
2100 A2=X1*PI*D2
2110 N1=N1*A2
2120 REM
2130 REM         BOILING HEAT TRANSFER COEFFICIENTS
2140 REM
2150 REM         POOL BOILING
2160 Z8=P(3,1)*H9/(H8/(P(1,1)-P(1,4)))↑0.5
2170 Z9=(P(2,1)/(H9*P3↑1.7*0.0133))↑3
2180 M3=Z8*Z9*A1*1054.8
2190 REM         FLOW BOILING
2200 Z7=(EXP(P9/900)/60)↑4
2210 N3=Z7*A2*B1*1000000
2220 REM
2230 REM          CALCULATE INITIAL HEAT TRANSFER COEFFICIENT
2240 REM          NON-ZERO PRIMARY VELOCITY CASE
2250 REM
2260 N2=0.023*(P(5,S2)/D2)*R1↑0.8*P4↑0.4*A2*B1
2270 REM
2280 REM          CALCULATE CONSTANT
2290 REM
2300 K2=B1*P(5,2)*PI*(D1↑2-D2↑2)/(4*X1)
2310 REM
2320 REM        READ IN TEMPERATURE DISTRIBUTION
2330 REM
2340 PRINT @U2:"NODE     TEMPERATURE, F"
2350 PRINT @U1:"INPUT INITIAL TEMPERATURE OF EACH NODE"
2360 FOR M=1 TO N
2370 PRINT @U1: USING 2390:"TEMPERATURE AT NODE ",M," F      ";
2380 INPUT T(M)
2390 IMAGE 20A,2D,8A
2400 PRINT @U2: USING 2410:M,T(M)
2410 IMAGE 1X,2D,9X,4D.2D
2420 NEXT M
2430 REM
2440 REM       ENTER NUMBER OF NODES WITH POWER
2450 REM
2460 PRINT @U1:"ENTER NUMBER OF POWERED NODES           ";
2470 INPUT A8
2480 FOR A9=1 TO N
2490 W1(A9)=0
2500 NEXT A9
2510 REM
2520 FOR A9=1 TO A8
2530 PRINT @U1:"POWERED NODE #                          ";
2540 INPUT W3
2550 W1(W3)=P1/A8
2560 NEXT A9
2570 REM
2580 REM         CALCULATE TEMPERATURE DISTRIBUTION ON SECONDARY SIDE
2590 REM
2600 REM          INITIALIZE TEMPERATURE BEFORE HEATER
2610 FOR M=1 TO W3
2620 T5(M)=T1
2630 PRINT @U2:T5(M)
2640 NEXT M
2650 REM         TEMPERATURE DISTRIBUTION AFTER HEATER
```

```
2660 W4=W3+1
2670 FOR M=W4 TO N
2680 W5=M-W3
2690 T5(M)=T1-W5*9*X1
2700 PRINT @U2:T5(M)
2710 NEXT M
2720 REM        PRINT HEADER
2730 PRINT @U2:"POINT      TEMPERATURE, F"
2740 REM
2750 REM      LOOP TO EVALUATE RESIDUES
2760 REM
2770 FOR M=1 TO N
2780 H1(M)=M1*ABS(T(M)-T5(M))↑0.25
2790 REM         CORRECT AREA AT THE HEATER REGIONS
2800 IF W1(M)<>0 THEN 2820
2810 GO TO 2840
2820 H1(M)=H1(M)*D5/D1
2830 REM
2840 H2(M)=N2
2850 IF R1>2100 THEN 2870
2860 H2(M)=H1*ABS(T(M)-T2)↑0.25
2870 Z5=T5(M)-T(M)
2880 IF M=1 THEN 2930
2890 IF M=N THEN 2950
2900 REM         COMPUTE RESIDUAL
2910 Q(M)=K2*(T(M-1)-2*T(M)+T(M+1))+H1(M)*Z5+H2(M)*(T2-T(M))+W1(M)
2920 GO TO 2960
2930 Q(M)=2*K2*(T(M+1)-T(M))+H1(M)/2*Z5+H2(M)/2*(T2-T(M))
2940 GO TO 2960
2950 Q(M)=2*K2*(T(M-1)-T(M))+H1(M)/2*Z5+H2(M)/2*(T2-T(M))
2960 NEXT M
2970 REM
2980 REM       LOOP TO SELECT LARGEST RESIDUAL
2990 REM
3000 R9=0
3010 FOR I=1 TO N
3020 C1=ABS(Q(I))
3030 IF C1>ABS(R9) THEN 3050
3040 GO TO 3070
3050 R9=Q(I)
3060 L1=I
3070 NEXT I
3080 V9=T(L1)
3090 REM
3100 REM         CALCULATE RELAXED TEMPERATURE WITH ZERO RESIDUAL
3110 REM
3120 J6=H1(L1)+H2(L1)
3130 IF L1=1 THEN 3180
3140 IF L1=N THEN 3200
3150 Z6=2*K2
3160 T(L1)=(W1(L1)+K2*(T(L1-1)+T(L1+1))+H1(L1)*T5(L1)+H2(L1)*T2)/(Z6+J6)
3170 GO TO 3230
3180 T(L1)=(4*K2*T(L1+1)+H1(L1)*T5(L1)+H2(L1)*T2)/(4*K2+J6)
3190 GO TO 3230
3200 T(L1)=(4*K2*T(L1-1)+H1(L1)*T5(L1)+H2(L1)*T2)/(4*K2+J6)
3210 REM PRINT RESULTS
3220 REM         CONVERGENCE CHECK
3230 V9=ABS(V9-T(L1))
3240 IF V9<0.1 THEN 3270
3250 GO TO 2770
3260 REM         WRITE OUT FINAL RESULTS
3270 FOR M=1 TO N
3280 REM
3290 REM         CONVERT TO DEGREES CENTIGRADE
3300 REM
3310 G(M)=(T(M)-32)/1.8
3320 PRINT @U2: USING 3330:M,T(M),G(M)
3330 IMAGE 1X,2D,9X,4D.2D,5X,4D.2D
3340 NEXT M
3350 END
```

```
THIS NODAL MODEL CALCULATES THE STEADY STATE
TEMPERATURES ALONG THE SURFACE OF A BOUNDARY
LAYER FLOW METER.

 1 IS ON THE PRIMARY SIDE

 3 IS THE SECONDARY SIDE FLUID

PIPE OUTER DIAMETER =  0.750 INCHES

PIPE WALL THICKNESS =  0.0490 INCHES

PRIMARY SIDE TEMPERATURE =  64.67 F

SECONDARY SIDE TEMPERATURE =  58.37 F

PRIMARY SIDE SATURATION TEMPERATURE = 208.00

SECONDARY SIDE SATURATION TEMPERATURE = 208.00

PRIMARY SIDE PRESSURE =   14.70 PSIA

PRIMARY SIDE WATER VELOCITY =  0.000 FT/SEC

HEATER POWER =  80.3 WATTS

16 NODES SPACED  0.250 INCHES APART

PRIMARY SIDE REYNOLDS NUMBER =        0.0

******* LAMINAR FLOW PRESENT *******
NODE     TEMPERATURE,°F
  1           60.00
  2           60.00
  3           60.00
  4           90.00
  5          150.00
  6          160.00
  7          150.00
  8          100.00
  9           70.00
 10           60.00
 11           60.00
 12           60.00
 13           60.00
 14           60.00
 15           60.00
 16           60.00
```

```
58.37
58.37
58.37
58.37
58.37
58.37
58.37
58.1825
57.995
57.8075
57.62
57.4325
57.245
57.0575
56.87
56.6825
POINT      TEMPERATURE, °F     °C
  1            72.96         22.75
  2            74.56         23.65
  3            84.29         29.05
  4           112.91         44.95
  5           199.24         92.91
  6           216.63        102.57
  7           199.19         92.88
  8           112.71         44.84
  9            83.63         28.68
 10            72.68         22.60
 11            68.13         20.07
 12            66.06         18.92
 13            65.07         18.37
 14            64.56         18.09
 15            64.37         17.98
 16            64.37         17.98
```